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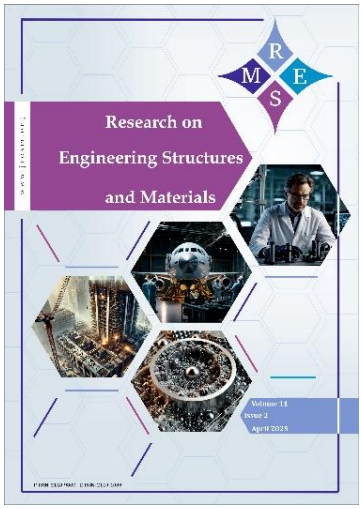

Durability and performance assessment of high-strength self-compacting concrete under environmental stressors

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Research Article

Durability and performance assessment of high-strength self-compacting concrete under environmental stressors

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Abstract

Self-compacting concrete (SCC) is widely acclaimed for its excellent flowability and capacity to compact exclusively under the power of gravity with no need for mechanical vibration. Yet, ensuring reproducible performance while minimizing typical problems like bleeding and segregation has long been a key concern. Addition of mineral admixtures such as ground granulated blast furnace slag (GGBFS), silica fume, and fly ash in the proportion of 5% to 30% has been found to improve the workability of the material and help in the production of high-strength types. This research investigates long-term durability properties of high-strength self-compacting concrete (HSSCC) in M60 and M70 grade, especially regarding resistance to environmental factors like acid attack, chloride and sulfate exposure, water absorption, effects of high temperatures, and rapid chloride ion penetration. The findings are reflective of high durability performance, especially among mixes with silica fume, which showed better densification of the matrix. Rapid Chloride Penetration Test (RCPT) results, as performed according to ASTM C1202, indicated that the concrete was of low permeability based on the finer pore structure imparted by the addition of silica fume and GGBFS. Overall, the results affirm the durability and resistance of the modified HSSCC under severe environmental exposure.

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1. Introduction

High-strength self-compacting concrete (HSSCC) achieves the benefits of high-performance concrete combined with enhanced flowability which guarantees successful placement even in highly reinforced structures. Nevertheless, its long-term performance in heavy environments is still challenged by durability problems like permeability, chloride ingress and chemical attack. In order to enhance the durability and sustainability of concrete, a number of Supplementary Cementitious Materials (SCMs) have been researched as cement substitutes to various degrees. Fly ash (FA), silica fume (SF), and ground granulated blast furnace slag (GGBFS) are some of them and are largely utilized because of their pozzolanic reactivity and filler properties. All of these materials play a distinct role in enhancing the mechanical and long-term performance of HSSCC: fly ash positively affects workability and long-term strength, silica fume positively affects densification of microstructure, and GGBFS positively affects resistance of chemical attack and chloride penetration. Also, the high cement content commonly used in HSSCC may predispose it to chemical attack and cracking owing to shrinkage in the event that it is not designed accordingly. A high-performance concrete with a water/binder ratio ranging between 0.30–0.40 is traditionally more resilient than typical concrete. It is the increased durability brought about not only by the

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decreased porosity but also by the partial disconnection of networks of capillaries and pores caused by self-desiccation [1]. Compressive strengths ranging between 65 and 85 MPa in 28 days have been observed in studies done on concrete with 30 and 40 percent fly ash of Western Australian Class F. Compared to control concrete of same strength the introduction of fly ash reduced drying shrinkage, and minimized sorptivity and chloride permeability at 28 days, and improved with time to 6 months. In general, the replacement of cement by fly ash increased the durability of the concrete [2]. In modern construction, concrete strength and durability have been increased significantly with blended cements, such as slag, fly ash, and silica fume, combined with modern admixtures, such as superplasticizers.

It is important to maintain the favorable rheological properties that will allow efficient and cost-effective concrete placement beyond simply the substitution rates or short-term strength [3]. General purpose Portland cement often takes the form of high-performance concrete that combines, as its admixtures, silica fume, slag and fly ash. It tests the mechanical and fresh properties of these combinations, for various applications. Although silica fume slightly decreased workability of GP cement mixes, silica fume greatly enhanced the mechanical properties of GP cement mixes and had a smaller effect on high slag cement mixes [4]. The primary practical use of SCM in concrete and cement is that, it is used to substitute some of the clinker in cement or cement itself, usually in order to make the material less expensive, greener, and more resistant to high loads and permanence. As of now, research is going on toward the identification of new materials, increasing replacement levels, enhancing testing procedures and changing the materials to incorporate performance enhancing additives [5]. HSC strengthened with steel fiber (SF) and carbon nanotube (HSCRSC) has excellent fluidity, strength, toughness, and longevity, and is suitable to be used in wellbores. Testing of 70 100 MPa HSCs indicated that fiber reinforcement increased compressive strength and switching of failure modes to ductile. Moreover, biaxial and triaxial compression strengths were greatly superior to the uniaxial compression strengths and the modified B3 offered the precise estimations of the shrinkage and creep at less than 6% error [6]. The rheological and compressive strength properties of SCC, as compared to the conventional, were also investigated in this study. V-funnel and L-box tests were used in assessing the flow properties of fresh concrete and its segregation resistance. SCC showed reduced early strength gain compared to traditional concrete, leading to reduced strength after 28 days although strength could be greater after 90 days [7]. The water/cement ratio exhibited a comparatively low influence on plastic properties of SCC in relation to the conventional concrete [8].

Durability of concrete is the ability to resist weather conditions and chemical exposure and abrasion resistance to its structural properties, is influenced by factors such as environmental conditions, intended use, and the nature of characteristic needed to enhance both strength and durability, RHA was applied partially to replace cement in M40 concrete (5-15%) in concrete. The workability tests showed that RHA had no influence on the concrete flow with 7.5% RHA giving optimal compressive strength. Durability tests such as resistance to acids, sulfates, alkaline as well as chlorides showed good performance. According to ASTM C1202, RCPT tests revealed that the penetration of chloride in the specimens was low to very low [11]. The experiment also evaluated the strength of SCC with the use of FAA as self-curing agents. FAA was pre-soaked 24 hours prior to mixing and scoria content was ranging between 5-20% and FAA at 15%. Tests were carried out to check the durability against salt attack, volume variation and UPV at 7, 28, 56, and 90 days on the hardened concrete. The findings indicated that substituting fine aggregate with pre-saturated scoria and FAA was effective in maintaining the strength as well as the durability of the concrete [12]. The industrial waste materials that can be utilized as alternative admixtures in concrete are silica fume, RHA, ferrochrome ash, and fly ash. The paper has determined that incorporation of small volumes of ferrochrome ash in 30 percent fly ash increases compressive strength extremely. Also, it also minimizes the emission of greenhouse gases and contributes to the management of waste, which facilitates sustainable construction [13]. Studied the durability properties of SCC, by adding the admixtures with ternary powder blends. SCC was produced with metakaolin, fly ash, and waste marble powder as replacements for cement and sand. Salhi et. al [14] investigated the influence of blended cements containing limestone and pozzolanic additions on the durability indicators of SCC. Use of fly ash-based Portland pozzolana cement with silica fume, metakaolin and

polycarboxylate ether were explored in SCC. They replaced SF, MK, or their mixtures with 5, 10, 15 and 20 percent of cement. Fresh properties were tested using a series of tests, which were relative to hardened properties, and some tests were followed by measurement of compressive and split tensile strength properties, and measurement of durability was then done [15]. Previous studies have examined the influence of these SCMs individually, showing that their inclusion significantly improves strength retention, reduces permeability, and enhances resistance to corrosive environments [2, 16,17]. Despite these advancements, further experimental validation is required to understand the individual contributions of each SCM to HSSCC's durability under varied exposure conditions [16][17].

1.1 Literature Review

Recent studies have explored the potential of various mineral and chemical admixtures to enhance the durability performance of self-compacting concrete (SCC). Pozzolanic cement significantly reduced sorptivity, water absorption, and porosity while improving resistance to sulfate and acid attack, demonstrating enhanced durability through microstructural refinement [14]. The inclusion of mineral powders significantly improved the concrete's resistance to permeability and chemical attack. Rajasekhar et. al [15] examined SCC produced with Portland Pozzolana Cement (PPC), supplemented with silica fume (SF), metakaolin (MK), and polycarboxylate ether (PCE) superplasticizer. The study involved partial replacement of PPC with MK, SF, and their combinations at 5–20% levels. Fresh property tests (slump flow, V-funnel, L- and U-box) and hardened property evaluations (compressive and split tensile strength) were conducted. Durability was further assessed through acid resistance, chloride penetration, and sulfate attack tests, with results confirming improved performance due to SCM inclusion. Murty et al. [18] stated that the combination of colloidal nano-silica in GGBFS-based SCC enhanced strength and durability over faster hydration, pore refinement as well as microstructural densification. Reddy et al. [19] recognized that nano-silica turns as both a nucleation site and a pozzolanic material, leading to improved C–S–H gel formation, condensed pore connectivity, and enhanced mechanical performance.

Table 1. Assessment of present study with previous literature

Study	Mix Composition	Tests Conducted	Key Findings	Advantage over Present Study
Nath & Sarker [2] – Cement & Concrete Composites	OPC + 20 % Fly Ash	Compressive strength, RCPT	Reported strength gain at later ages and moderate chloride resistance in high-volume fly-ash concrete.	Limited to a single SCM; no multi-admixture synergy studied.
Toutanji et al. [16]– Construction & Building Materials	OPC + 15 % Silica Fume	SEM, RCPT	Observed microstructural densification and very low chloride penetration due to pozzolanic reaction of silica fume.	Did not evaluate chemical or acid resistance.
Rajasekar et al. [17]– Journal of Building Engineering	OPC + 40 % GGBFS	RCPT, Sulphate resistance	Demonstrated improved chemical durability and long-term stability of GGBFS-based SCC mixtures.	Freeze–thaw and multi-environmental effects not considered.
Present Study	OPC + 15 % Fly Ash + 10 % Silica Fume + 20 % GGBFS	Compressive strength, RCPT, Chemical attack (HCl, H_2SO_4, $MgSO_4$, NaCl)	Exhibited enhanced strength retention, very low chloride ingress, and reduced weight loss under multiple stressors.	Evaluates combined SCM synergy and multi-environmental durability in HSSCC.

Gnanaraj et al. [21] developed SCC using fly ash and ultra-fine natural steatite powder (UFNSP) in ternary blends. Cement was replaced partially with fly ash (10% and 20%), and UFNSP was added

in varying dosages up to 25%. Durability measures were checked, such as porosity, water absorption, sorptivity, and rapid chloride permeability. The optimum blends minimized microcracks and pore connectivity, which were verified by SEM analysis as well as formation of magnesium silicate hydrate phases, which led to denser matrix. Aziz et al. [22] explored blended supplementary cementitious materials in self-compacting concrete to improve sustainability and engineering performance. The findings indicated that fine-tuning these materials improved workability, strength development, and durability through enhanced particle packing and matrix densification, decreasing cement usage. The comparative analysis (Table 1) shows that earlier researchers mainly studied the effects of individual supplementary cementitious materials like fly ash, silica fume, or GGBFS on the durability performance of concrete at a given exposure condition. Conversely, the current experiment incorporates various SCMs in a combined framework, and it is possible to synergistically improve both mechanical and durability properties in different environmental stress conditions. This holistic approach offers greater practicality for applications to aggressive service environments like marine and industrial environments. Table 1 provides a comparative overview of the literature.

1.2 Statement of The Problem

Despite the number of studies examining the impact of individual SCMs on the characteristics of high-strength concrete, including fly ash, silica fume, and GGBFS, there is still a lack of understanding of the individual impact of each material on the durability in various environmental conditions. Most past studies have concentrated on compressive strength or chloride resistance individually rather than including other attributes of durability, like acid resistance,, sulphate resistance, weight loss, or long-term permeability. Such a deficiency of systematic knowledge limits the optimal application of individual SCM to particular durability demands. Hence, this research is aimed at comparing and assessing the respective individual impact of fly ash, silica fume, and GGBFS on the mechanical and durability properties of HSSCC with special reference to the resistance to the penetration of chlorides and chemical attacks under controlled laboratory conditions.

1.3 Research Objectives

The current research intends to examine the stability and performance of High-Strength Self-Compacting Concrete (HSSCC) under extreme environmental aggressors using a number of short-term accelerated and simulated long-term exposure tests. With the identified research gap, the specific objectives were developed as follows:

- To establish and assess HSSCC mixes with optimal mix proportions to represent high strength and durability performance. To investigate the resistance of HSSCC to different stress is durability including:
- Chloride penetration test which is measured on Rapid Chloride Penetration Test (RCPT) and salt ponding.
- Sulphate attack test was determined by the loss of mass and expansion.
- Acid resistance has been examined on the basis of mass loss and visible surface degradation.
- To compare performance of the HSSCC and that of normal-strength self-compacting concrete (SCC) and conventional high-performance concrete (HPC) under the same testing conditions.

1.4 Novelty and Research Significance

This study develops an all-inclusive durability evaluation framework of High-Strength Self-Compacting Concrete (HSSCC) that has been subjected to various loadings in the environment. The research employs new methods to improve the accuracy of the service situation in the real world and the validity of performance assessment:

- Hybrid SCM blending: It is made using optimized ratios of fly ash, silica fume, and ground granulated blast-furnace slag (GGBFS), to refine the pore structure, lower permeability, and enhance chemical attack resistance.

- Multi-aggressor assessment: Durability testing is not limited to any single exposure conditions but includes chloride, sulphate and acid environments to mimic the realistic degradation and to give a comprehensive profile of durability.
- Comparative benchmarking: HSSCC behavior is equated with that of normal self-compacting concrete (SCC), and high-performance concrete (HPC) behavior under the same exposure conditions, which allows easy evaluation of the relative merits of the behavior in strength retention and degradation resistance.

Generally, this study will be helpful in developing a methodological approach to durability assessment of sustainable and high-performance concrete in strong environments like coastal area, industrial area and cold climate areas. Overall, this investigation contributes to the development of a systematic durability evaluation approach for sustainable, high-performance concrete suitable for aggressive environments such as coastal, industrial, and cold-weather regions.

2. Materials

In the study, OPC grade 53 was chosen to comply with the IS:12269-1987 (9) requirements, providing cement of a high quality, with similar performance when used in buildings. The fine aggregate was river sand which is categorized as zone-II as per IS:383-1970 (10). This sand is best suited in concrete because it offers a balanced grading which adds to overall workability and strength of the mix. Crushed granite (12 mm) was selected as coarse aggregate, and it meets the standard requirements of the hardness, durability, and angularity that are important in the design of a robust and stable concrete matrix in accordance with the standards of IS 383: 1970 (10). In order to improve the performance of concrete, the byproducts of the different industries were used as partial replacements to the cement. Silica fume, fly ash, and GGBFS were added to the mixture at different concentrations (between 5 and 30 percent) of thermal power plants, ferrosilicon and steel manufacturing plants, respectively. The materials have been selected due to the following positive qualities: fly ash enhances workability and heat of hydration, silica fume adds strength and durability by improving pore structure, and GGBFS prevents chemical attack and permeability. The angular shape of these cementitious additives adds a lot to the overall strength development of the high-performance concrete since the angularity improves the mechanical interlocking of the particles. Moreover, the blend also included a superplasticizer (Glenium B233) and a viscosity-modifying agent (Glenium Stream2). The superplasticizer enhanced fluidity of the concrete without raising the amount of water in it hence maintaining the low water-cement ratio needed to create high-strength concrete. The viscosity-modifying agent was employed to make the mix stick together to overcome such problems as segregation and bleeding that may happen with high-flow concretes. With this balanced mix of materials and additives, it was properly planned to include high-performance concrete with high strength and durability, and workability to satisfy the construction standards of the day.

3. Experimental Procedure

Standard tests were conducted on typical specimens using the Indian standards of durability to determine the behavior of HSSCC in different situations. The angular shape of these cementitious additives and sulfate attack and high temperatures, the RCPT and the water absorption. It concentrated on mixes that had good mechanical performances. The study involved conventional mixes for grades M60 and M70, as well as blends with 20% fly ash, 10% silica fume, and 15% GGBFS, corresponding to the conventional grades of concrete. The specific mixes tested were CSC-60, SCF60-20, SCS60-10, SCG60-15, CSC-70, SCF70-20, SCS70-10, and SCG70-15. Water curing spectrum of the cube specimens for 28 days before immersion into acid, chloride, and sulfate solutions for 30, 60 and 90 days. Compressive strength and periodic weight for the specimens which were refreshed every two weeks to ensure the solutions were still effective. RCPT of the concrete was done on cylindrical discs and water absorption test done on cube specimens to determine the permeability of the concrete.

3.1 Rationale for Selection of SCM Proportions

The percentage of supplementary cementitious materials (SCMs) constituting 10% silica fume, 15% ground granulated blast furnace slag (GGBFS) and 20% fly ash was chosen in this paper in relation to their respective as well as combined effects on the concrete durability, workability and mechanical performance. Silica Fume (10%) is characterized by a high reactivity of pozzolana and the ultrafine particle size, which significantly leads to the improvement of the microstructure of concrete by decreasing the porosity and increasing the interfacial transition zone (ITZ). It has been demonstrated that a 10% replacement level is the optimal level to maximize these benefits and not to affect workability. Research has established that silica fume with this dosage is effective in enhancing the chloride penetration and acid attack resistance, and therefore, it can be used in hostile environments.

GGBFS helps in long-term strength equipment and improves sulfate resistance because of the latent hydraulic characteristics. A 15% replacement will provide a balance between long life and youthful power. It has been found that, GGBFS enhances the ability of the concrete to resist chemical attack and it also lowers the heat of hydration, which is advantageous in the mass concrete practices. Fly Ash (20%) is highly spherical in nature and its pozzolanic reaction is slow therefore it enhances workability and also provides long term durability. A replacement level of 20 percent has gained a lot of acceptance in high performance concrete with the aim of decreasing permeability and increasing resistance to chloride intrusion. The dosage is also in line with sustainable building practices since it minimizes cement. The chosen proportions are justified by the existence of the prior experimental projects, which tested such compositions and indicated the improvement of such durability parameters as the lower values of rapid chloride permeability (RCPT), higher compressive strength, and decreased water absorption rates.

3.2 Experimental Design and Control of Environmental Variables

To measure the high strength self-compacting concrete (HSSCC) durability in the aggressive conditions of the environment, the specimens were immersed in three different solutions: sulfuric acid (H_2SO_4) and sodium chloride (NaCl) and sodium sulphate (Na_2SO_4). These solutions had concentrations that were chosen with close care to reflect realistic exposures in the situations that are likely to occur in industrial, coastal and sulphate-rich environments. Particularly, the solution was made using sulfuric acid with concentration of 5% by volume, with the pH that was kept at the range of 2.0-2.5 during the soaking time. This was done by constant monitoring with a calibrated digital pH meter and by adding dilute acid to the solution when necessary to overcome the buffering effect of leaching concrete ions.

The sodium chloride solution was held at 3.5 percent/kg, which is a salt concentration where sea water is found and the sodium sulphate solution was set at 5 percent/kg to simulate the conditions found in the soil or ground water of a high-sulphate concentration. The chloride and sulphate solutions were replenished weekly so that there were constant ionic concentrations and that the solutions were not depleted by chemical reactions with the concrete matrix. Each specimen was completely covered in the solution of the solutions at ambient laboratory temperature (25 ± 2°C) for 90 days. The soaking containers were covered so as to reduce evaporation and contamination and the exposure regime was kept constant in all mixes so that reproducibility of results is possible and the effect of binder composition on the performance of the durability is isolated.

4. Results and Discussion

4.1 Acid Attack Test

This study paper involved an acid attack test on standard 150mm cube specimens to determine their ability to resist acidic environment. The cube compressive strength meant was measured following 28-day water curing (NWC) and subsequently after being exposed to an acid medium on 30, 60 and 90 days. Moreover, the proportional weight loss as a result of being exposed to acid was noted. The findings, shown in Table 2 provide information on the stability of concrete mixes in acidic conditions. Tests conducted on the specimens are CSC-60, SCF60-20, SCS60-10, SCG60-15, CSC-70, SCF70-20, SCS70-10, and SCG70-15. These specimens had compressive strengths of 66.1

MPa, 67.8 MPa, 68.1 MPa, 67.9 MPa, 75.9 MPa, 76.8 MPa, 78.4 MPa, and 77.8 MPa after 28 days of water curing, respectively. After 30 days at an acid medium, compressive strengths dropped to 63.2 MPa, 64.9 MPa, 65.4 MPa, 65.1 MPa, 72.4 MPa, 73.4 MPa, 75.2 MPa and 74.5 MPa. These values show a decrease of 4.39, 4.28, 3.96, 4.12, 4.61, 4.43, 4.08 and 4.24 respectively of their strengths after normal curing.

The first decrease indicates the sensitivity of the material to acid attacks, albeit the reduction is not that strong. The compressive strength at acid immersion at 60 days was 57.9 MPa, 59.9 MPa, 60.9 MPa, 60.4 MPa, 66.7 MPa, 67.7 MPa, 70.2 MPa and 69.0 MPa. These decreases of these strengths, or 12.41, 11.65, 10.57, 11.05, 12.12, 11.85, 10.46, 11.31, are all lower than after normal cure. The greater reduction shows the further worsening of the concrete structural integrity as the time of exposure in the acidic environment increases. The compressive strengths were further reduced to the level of 52.1 MPa, 53.8 MPa, 54.6 MPa, 54.1 MPa, 58.5 MPa, 59.8 MPa and 61.5 MPa, of the first 90 days of acid immersion. The 21.18, 20.65, 19.82, 20.32, 22.92, 22.14, 21.56 and 21.98 MPa respectively, are strength of these results reduced by normal curing values of specimens. This is especially true in the case of structures that might be subjected to such conditions as the high propensity of a loss in strength through a long-term exposure to acid justifies the choice of material with higher resistance to acid attack.

The continuous loss of weight with time is a gradual deterioration of the concrete matrix by the action of the acid which gradually attacks the material. Overall, these findings suggest that there is a risk to select and compose concrete mixtures with a higher resistance to the assault of acid, in particular, in the situations when the material under consideration is exposed to the acidic climate over an extended period of time. The data also claim that tested concrete mixtures lose strength and mass over time and that the rate at which they contribute to the deterioration is not even, but introduction of SCMs can support in minimizing undesirable outcomes of the exposure on acids.

Table 2. Acid attack test results

Mix ID	Compressive strength in MPa (at the day of)				% of loss in compressive strength (at the day of)		
	NWC	30	60	90	30	60	90
CSC-60	66.1	63.2 ± 2.89	57.9 ± 8.2	52.1 ± 14	4.39	12.41	21.18
SCF60-20	67.8	64.9 ± 2.89	59.9 ± 7.9	53.8 ± 14	4.28	11.65	20.65
SCS60-10	68.1	65.4 ± 2.69	60.9 ± 7.2	54.6 ± 13.5	3.96	10.57	19.82
SCG60-15	67.9	65.1 ± 2.80	60.4 ± 7.50	54.1 ± 13.8	4.12	11.05	20.32
CSC-70	75.9	72.4 ± 3.5	66.7 ± 9.2	58.5 ± 17.4	4.61	12.12	22.92
SCF70-20	76.8	73.4 ± 3.39	67.7 ± 9.09	59.8 ± 17	4.43	11.85	22.14
SCS70-10	78.4	75.2 ± 3.2	70.2 ± 8.2	61.5 ± 16.9	4.08	10.46	21.56
SCG70-15	77.8	74.5 ± 3.3	69 ± 8.8	60.7 ± 17.1	4.24	11.31	21.98

Table 3. Percentage loss in weight test results due to acid attack

Mix ID	% of loss in weight at the day of			
	0	30	60	90
CSC-60	0	4.22	6.28	8.11
SCF60-20	0	4.13	6.01	7.98
SCS60-10	0	3.85	5.84	7.65
SCG60-15	0	4.03	5.96	7.82
CSC-70	0	4.38	6.36	8.18
SCF70-20	0	4.24	6.13	8.02
SCS70-10	0	4.02	5.95	7.81
SCG70-15	0	4.19	6.02	7.95

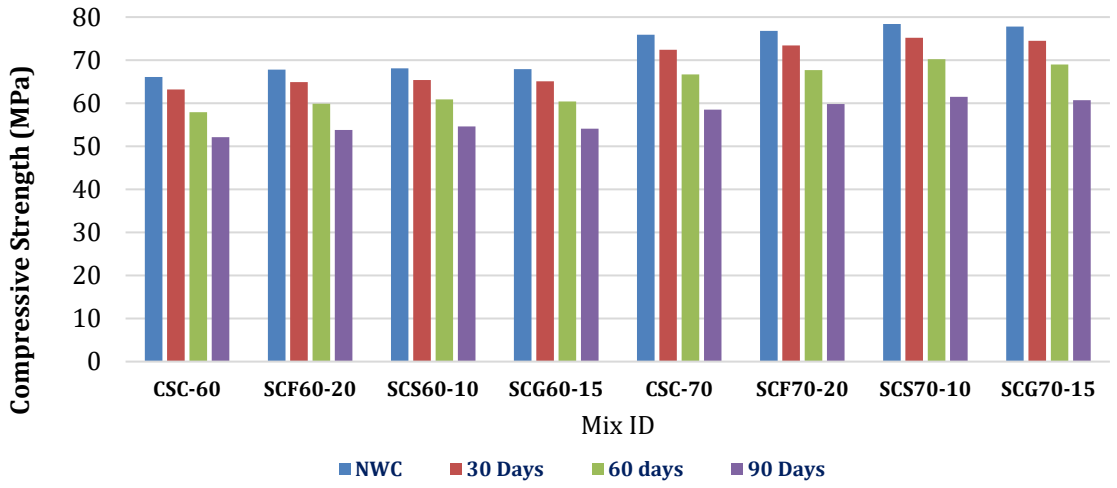

Fig. 1. Compressive strength variation with exposure duration for acid attack

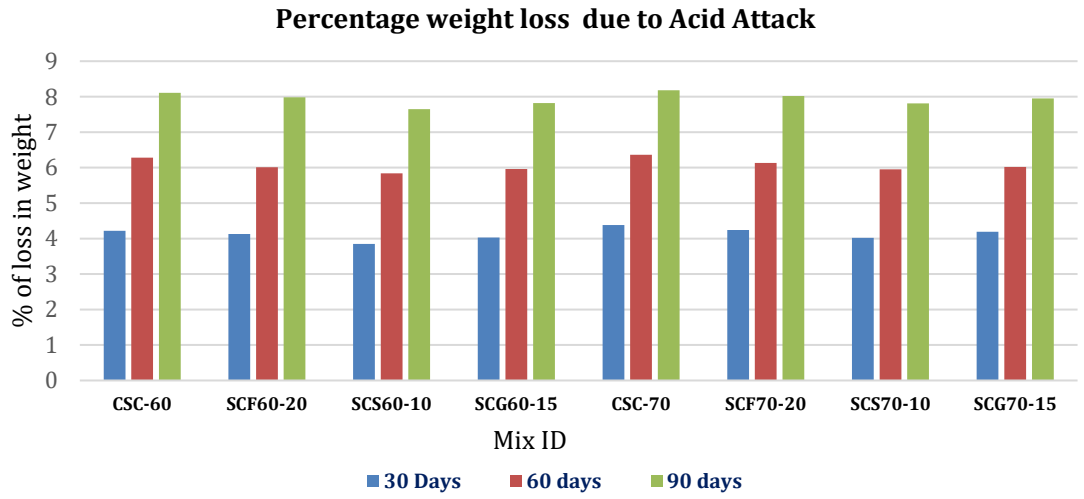

Fig. 2. Percentage weight loss with exposure duration for acid attack

4.2 Chloride Attack Test

The test was performed on standard 150 mm cube specimens to assess their performance regarding the resistance to degradation caused by chloride. The compressive strength of the specimens was determined after a normal 28 days water curing (NWC) and that after 30-, 60- and 90-days immersion under a chloride medium. The proportionality of the weight loss as a result of the chloride attack was also measured and the results are as presented in Table 4. The initial compressive strengths of CSC-60, SCF60-20, SCS60-10, SCG60-15, CSC-70, SCF70-20, SCS70-10, and SCG70-15 specimens, 28 days water curing, and after 28 days, were 66.1 MPa, 67.8 MPa, 68.1 MPa, 67.9 MPa, 75.9 MPa, 7 The compressive strengths reduced a little to 65.9 MPa, 67.6 MPa, 68.0 MPa, 67.8 MPa, 75.6 MPa, 76.6 MPa, 78.3 MPa, and 77.7 MPa after 30 days of being exposed to the chloride medium. These are relatively small, ranging between 0.13 and 0.40 per cent less than the respective compressive strengths following normal curing, suggesting that the effects of the chloride attack on the concrete as far as strength is concerned are relatively low. The compressive strengths of the chloride medium further reduced after 60 days to 61.8 MPa, 64.1 MPa, 65.3 MPa, 64.9 MPa, 71.6 MPa, 73.1 MPa, 75.2 MPa and 74.2 MPa. These values are however a greater decrease than in the instance of the strengths after normal curing, not at 4.08 but at 6.51. This reduction depicts that the length of exposure to the chloride has a more severe bearing on the integration of the concrete and perhaps with time, it leads to the erosion of the material. The compressive strength after 90 days in the chloride medium fell to another extent of 57.8 MPa, 60.3 MPa, 61.8

MPa, 60.8 MPa, 66.9 MPa, 68.4 MPa, 70.6 MPa, and 69.7 MPa. This continued degradation was confirmed by the now reduced range of compressive strength reduction from 9.25% to 12.56%. These results emphasize the need to develop concrete with better chloride resistance, especially for the structures in environments where the salt content is high or there is deicing salt.

Table 4. Chloride attack test results

Sl No	Mix ID	Compressive strength in MPa (at the day of)				% of loss in compressive strength (at the day of)		
		NWC	30	60	90	30	60	90
1	CSC-60	66.1	65.9±0.2	61.8±4.3	57.8±8.3	0.30%	6.51%	12.56%
2	SCF60-20	67.8	67.6±0.2	64.1±3.7	60.3±7.5	0.29%	5.46%	11.06%
3	SCS60-10	68.1	68±0.1	65.3±2.8	61.8±6.3	0.15%	4.11%	9.25%
4	SCG60-15	67.9	67.8±0.1	64.9±3	60.8±7.1	0.15%	4.42%	10.46%
5	CSC-70	75.9	75.6±0.3	71.6±4.3	66.9±9	0.40%	5.67%	11.86%
6	SCF70-20	76.8	76.6±0.2	73.1±3.7	68.4±8.4	0.26%	4.82%	10.94%
7	SCS70-10	78.4	78.3±0.1	75.2±3.2	70.6±7.8	0.13%	4.08%	9.95%
8	SCG70-15	77.8	77.7±0.1	74.2±3.6	69.7±8.1	0.13%	4.63%	10.41%

Table 5. Percentage loss in weight test results due to chloride attack

Sl No	Mix ID	% of loss in weight (%) at the day of			
		0	30	60	90
1	CSC-60	0	3.34	4.94	6.28
2	SCF60-20	0	3.14	4.68	6.12
3	SCS60-10	0	2.44	3.59	5.43
4	SCG60-15	0	2.91	4.08	6.01
5	CSC-70	0	3.41	4.89	6.31
6	SCF70-20	0	3.18	4.72	6.19
7	SCS70-10	0	2.53	4.01	5.73
8	SCG70-15	0	2.86	4.41	6.11

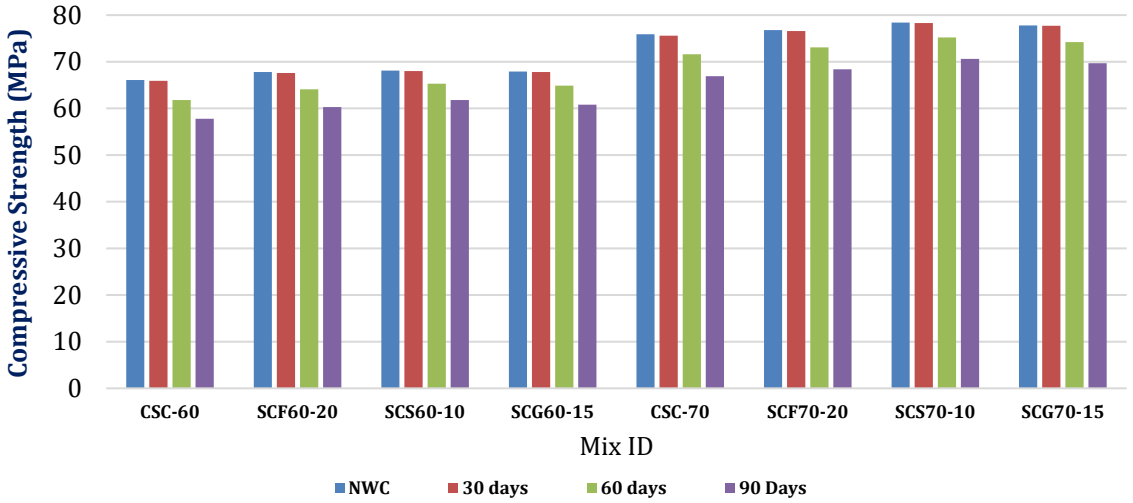

Fig. 3. Compressive strength variation with exposure duration for chloride attack

Table 5 includes monitoring of the weight loss due to chloride attack in addition to compressive strength. After 30 days of exposure, the percentages for the weight loss with the CSC-60, SCF60-20, SCS60-10, SCG60-15, CSC70, SCF70-20, SCS70-10, and SCG70-15 specimens were 3.34%, 3.14%, 2.44%, 2.91%, 3.41%, 3.18%, 2.53%, and 2.86%, respectively, and remained modest. The initial loss of weight found is associated with the release of chloride-sensitive components of the concrete. Upon day 60, the weight loss was increased to 4.94%, 4.68%, 3.59%, 4.08%, 4.89%, 4.72%, 4.01%, and 4.41% respectively, indicating the continued deterioration of physical integrity of the concrete

due to chloride exposure. Over the course of 90 days, the percentage weight loss rose to 6.28%, 6.12%, 5.43%, 6.01%, 6.31%, 6.19%, 5.73%, and 6.11% and continued degradation of the concrete material due to chloride exposure.

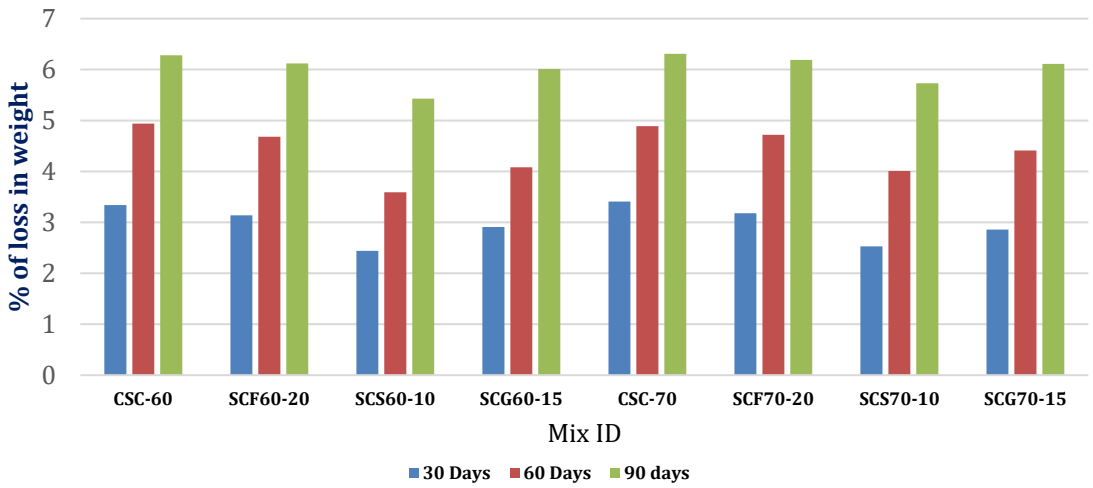

Fig. 4. Percentage weight loss with exposure duration for chloride attack

Figure 3 illustrates compressive strength variation with exposure duration, while Fig. 4. shows percentage weight loss trends due to chloride attack. Overall, the results of the chloride attack test indicate that the concrete specimens exhibit a former ability to resist chloride induced strength loss; however, prolonged exposure results in large decreases in both strength and in weight. Degradation extent is different between different concrete mixes and it is thought that some mixtures may be more resistant to chloride attack. Which emphasizes the necessity of materials and mix designs chosen carefully in environments where chloride exposure takes place.

4.3 Sulphate Attack Test

A sulfate attack experiment was conducted on standard 150mm cubes, in order to determine the durability of the cubes and their resistance to the effects of sulfate deterioration. It was conducted by measuring compressive strength of cubes at the end of standard 28 days of water curing (NWC), followed by 30, 60 and 90 days of the immersion in a sulfate solution. The %age of sulfate attack on weight loss was also reported. These tests were summarized in Table 6. First, compressive strengths of CSC-60, SCF60-20, SCS60-10, SCG60-15, CSC-70, SCF70-20, SCS70-10, and SCG70-15 specimens were 66.1 MPa, 67.8 MPa, 68.1 MPa, 67.9 MPa, 75.9 MPa, 76.8 MPa, 78.4 MPa and 77.8 MPa. The compressive strengths of these specimens however reduced slightly after 30 days of exposure to the sulphate medium to 65.1 MPa, 66.8 MPa, 67.2 MPa, 67.0 MPa, 74.5 MPa, 75.7 MPa, 77.6 MPa, and 76.9 MPa respectively. The decreases in these strengths were between 1.02-1.84 %, which means that there was a slight initial effect of the exposure to sulphates on the compressive strength of the concrete after 60 days in the sulphate medium, and the compressive strengths of the specimens were further decreasing to 60.6 MPa, 62.2MPa, 63.4MPa, 62.8MPa, 69.1MPa, 70.3MPa, 72.1MPa, and their strength reduction was now between 6.90 and 8.96 % indicating a bigger corrosion of the concrete since it had been exposed to sulphates over a longer period. Lastly, the compressive strengths decreased to 53.8 MPa, 56.7 MPa, 58.2 MPa, 57.1 MPa, 62.5Mpa, 64.3Mpa, 66.6Mpa and 65.2Mpa after 90 days of immersion in the medium of sulphate. These reductions of 14.54% to 18.61% signify a significant reduction in the concrete strength, and the consequences of the long-term harmful impact of sulphate on the concrete matrix. Besides compressive strength, the weight loss as a result of sulphate attack of the specimens also measured and reported in Table 7.

The weight loss in the CSC-60, SCF60-20, SCS60-10, SCG60-15, CSC-70, SCF70-20, SCS-70-10, and SCG70-15 after 30 days exposure to sulphates was 3.58, 3.34, 2.94, 3.12, 3.68, 3.39, 3.01 and 3.28 respectively. This primary loss of weight is the first sign of chemical degradation of the concrete

since the sulphates start attacking the cementitious materials. The weight loss was also enhanced to 5.43, 5.02, 4.28, 4.91, 5.39, 5.13, 4.87 and 5.03 after 60 days of immersion in the sulphate medium. The weight loss increase is thus due to the continuous degrading of the concrete as the sulphate ions are still reactive to the components in the concrete and cause further degradation. The subjects had lost weight in the amount of 7.01, 6.82, 6.02, 6.39, 6.99, 6.56, 6.11, and 6.48 at the end of the 90-day exposure. The outcomes that have been achieved on the basis of these tests confirm that sulphates can indeed result in the loss of the material in the long run and hence compromise the structure of concrete.

Table 6. Sulphate attack test results

Sl No	Mix ID	Compressive strength in MPa (at the day of)				% of loss in compressive strength (at the day of)		
		NWC	30	60	90	30	60	90
1	CSC-60	66.1	65.1±1	60.6±5.5	53.8±12.3	1.51%	8.32%	18.61%
2	SCF60-20	67.8	66.8±1	62.2±5.6	56.7±11.1	1.47%	8.26%	16.37%
3	SCS60-10	68.1	67.2±0.9	63.4±4.7	58.2±9.9	1.32%	6.90%	14.54%
4	SCG60-15	67.9	67±0.9	62.8±5.1	57.1±10.8	1.33%	7.51%	15.91%
5	CSC-70	75.9	74.5±1.4	69.1±6.8	62.5±13.4	1.84%	8.96%	17.65%
6	SCF70-20	76.8	75.7±1.1	70.3±6.5	64.3±13.4	1.43%	8.46%	16.28%
7	SCS70-10	78.4	77.6±0.8	72.1±6.3	66.6±11.8	1.02%	8.04%	15.05%
8	SCG70-15	77.8	76.9±0.9	71.1±6.7	65.2±12.6	1.16%	8.61%	16.20%

Table 7. Percentage loss in weight test results due to sulphate attack

Sl No	Mix ID	% of loss in weight (%) at the day of			
		0	30	60	90
1	CSC-60	0	3.58	5.43	7.01
2	SCF60-20	0	3.34	5.02	6.82
3	SCS60-10	0	2.94	4.28	6.02
4	SCG60-15	0	3.12	4.91	6.39
5	CSC-70	0	3.68	5.39	6.99
6	SCF70-20	0	3.39	5.13	6.56
7	SCS70-10	0	3.01	4.87	6.11
8	SCG70-15	0	3.28	5.03	6.48

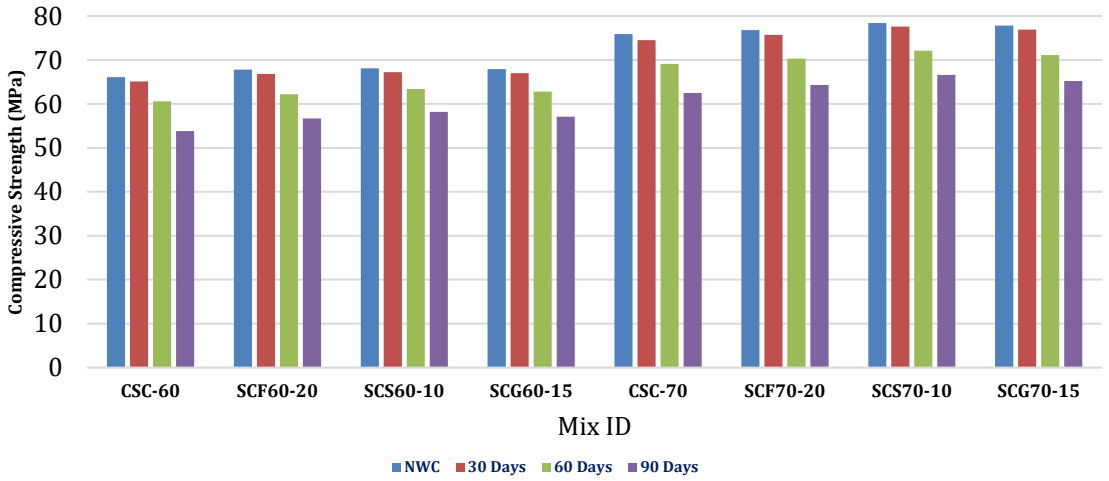

Fig. 5. Compressive strength variation with exposure duration for sulphate attack

Figure 5 demonstrates compressive strength variation with exposure duration, while Fig. 6. shows percentage weight loss trends due to sulphate attack. Results of the sulphate attack test indicate that concrete withstands initially the sulphate induced damage but in case of extended exposure, the compressive strength and weight parameters dropped decrease. The degradation in relation to concrete mix is also exhibited and it is concluded that the destruction caused by sulphate is highly

dependent on the materials used, whether they are sulphate resistant or not and also with regard to the mix design when sulphate is anticipated. This test emphasizes the necessity of the selection of proper chemical resisting materials and the mix design that will lead to a long-term durability and performance of concrete exposed to aggressive chemical environment.

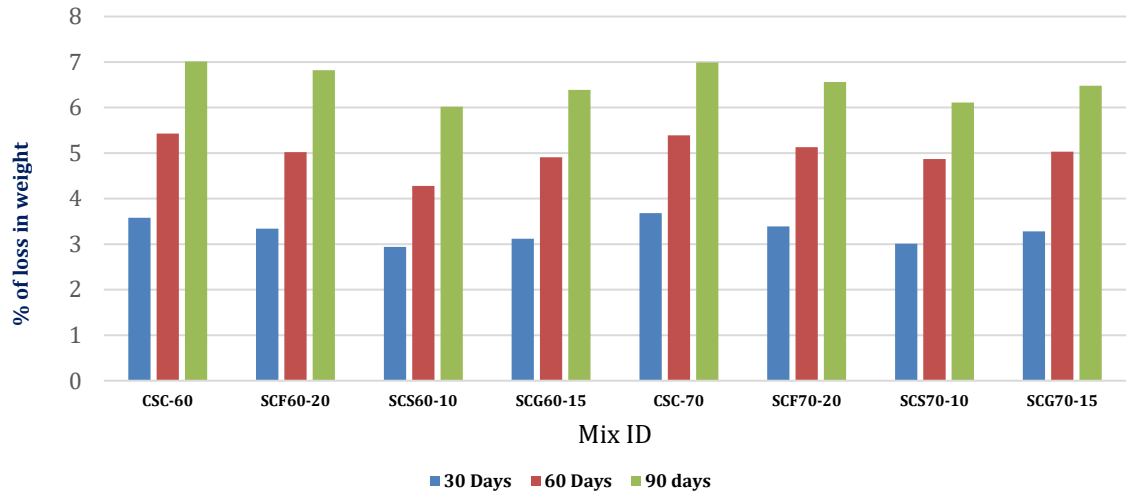

Fig. 6. Percentage weight loss with exposure duration for sulphate attack

The high-strength self-compacting concrete (HSSCC) in the real-world application and how it is suitable, in particular to marine infrastructure, fertilizer production facilities, and drainage systems, where chloride, sulphate and acidic environments are common. The increased durability in our investigation indicates that SCM-modified HSSCC may have a high potential to increase structural service life and decrease the frequency of maintenance thus lifecycle performance and cost-effectiveness. As well, the experimental findings verify that the SCM-based HSSCC has a high chloride ingress/chemical attack resistance. Its properties render it very appropriate in marine buildings (ports, jetties, offshore platforms), fertilizer plants and urban drainage systems, where exposure to aggressive ions is inevitable. The lower permeability guarantees the long life of use and reduced maintenance frequency, which is of huge economic and environmental advantage.

4.4 Rapid Chloride Penetration Test

The Rapid Chloride Penetration Test (RCPT) was performed on cylindrical disc specimens measuring 100 mm in diameter and 50 mm in thickness. This test evaluates concrete quality by quantifying chloride ion permeability through the measurement of electrical charge passed, expressed in coulombs. The presence of pores is high when the RCPT values are high and the concrete is designated under poor quality. When the RCPT values are low which means the presence of pores is also low in quantity and so the current voltage value is also low which indicates the concrete is made with good quality. The electrical charge passed during RCPT is reported in coulombs and classified according to ASTM C1202 and the results are summarized in Table 8. According to ASTM C1202, conventional Concrete and SCF70-20 specimens will be classified as Low. This categorization implies that the mixes of concrete used in this case have a comparatively high resistance to the penetration of chloride ions implying that the concrete mixes contain fewer pores, and therefore, more resistant to chloride-related degradation.

Table 8. RCPT values of HSSCC

Mix ID	Charge Passed in Coulomb	Recommendation as per ASTM C1202
CSC-60	1228 ± 110	1000-2000 - Low
SCF60-20	994 ± 85	100-1000 - Very Low
SCS60-10	768 ± 75	100-1000 - Very Low
SCG60-15	848 ± 82	100-1000 - Very Low
CSC-70	1109 ± 105	1000-2000 - Low
SCF70-20	1021 ± 88	1000-2000 - Low
SCS70-10	762 ± 74	100-1000 - Very Low
SCG70-15	821 ± 80	100-1000 - Very Low

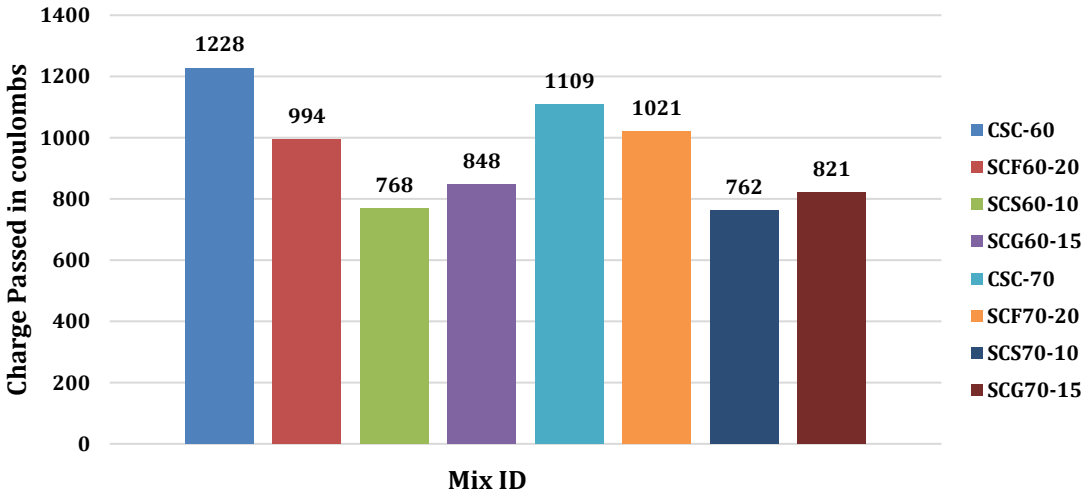

Fig. 7. RCPT results of HSSCC

Other Specimens are classified as very Low. This classification is an indicator of even improved performance with little penetration of chloride ion which depicts the very low presence of pores and high-quality concrete mix. RCPT findings indicate that the standard concrete and the SCF70-20 mix has sufficient resistance to the penetration of chloride ions and satisfies the requirements of the Low category. In the meantime, the other mixes have better performance as they have the best classifications of Very Low indicating that they are highly resistant to chloride attack. Chloride ion penetration was significantly lowered by the addition of silica fume and GGBFS. Fig. 7. provides a bar chart of the values of charges in all mixtures, making it evident that SCM-based HSSCC with an improved resistance is the illustration of the successful quality and durability of analyzed concrete samples. The findings of the study show that high-strength self-compacting concrete (HSSCC) with fly ash, silica fume and GGBFS exhibited a much higher strength and durability than that of the control mix. This increase in performance could be explained by the pozzolanic reaction and filler effect of the SCMs that polished the pore structure and formed more C-S-H gel.

The results of RCPT showed that total charge passed on SCM-blended concretes was significantly lower and they fell within the category of low to very low permeability per ASTM C1202. This proves the enhanced resistance towards chloride penetration and also signifies denser and less interconnected pore network. The peer-reviewed works have been cited in order to support these observations. Similar results were previously reported [2, 16,17] where silica fume and GGBFS were observed to lower the pore connectivity, interfacial transition zone strength and resistance to aggressive ions. These findings seem to confirm the current findings, indicating that the enhanced durability of HSSCC can be in large part attributed to the collective microstructural refinement that has been reached by the use of composite SCMs. Also, the chemical exposure tests (HCl, H_2SO 4, $MgSO_4$, and NaCl) demonstrated that the weight loss and strength retention were lower in the mixes prepared with SCM, which is why they can be used in the construction of structures exposed to severe conditions, including coastal, marine, and industrial environments. It was demonstrated in recent experimental studies that nano-silica and GGBFS enhance microstructural densification in SCC systems [18,19] and reviews underscore the importance of binder chemistry and refinement of pores on long-term durability [20].

4.5 Water Absorption Test

High quality concrete must have low permeability. To test HSSCC, a water absorption test was conducted on a cylindrical disc with a thickness of 50 mm and a diameter of 100.00 mm and as per ASTM C 140. Results are shown in Table 9. The absorption of water is monitored according to the ASTM C 140 requirements. The average water absorption should not be absorbed by the tested samples at an average of more than 5%. Besides this, it should be possible in no single specimen to achieve an absorption of not more than 7 percent of water. All the tested samples met these requirements implying that the rates of water absorption are acceptable. The findings indicate that

the concrete is high quality and hardy in addition to being of low permeability. The HSSCC samples also satisfy the standard requirements of the ASTM C 140 and as such, there is an overall water absorption of less than 5% and no single sample is higher than 7%.

Table 9. Water absorption values of HSSCC

Mix ID	Water Absorption (%)
CSC-60	2.84
SCF60-20	2.31
SCS60-10	1.46
SCG60-15	1.96
CSC-70	2.78
SCF70-20	2.52
SCS70-10	1.78
SCG70-15	2.03

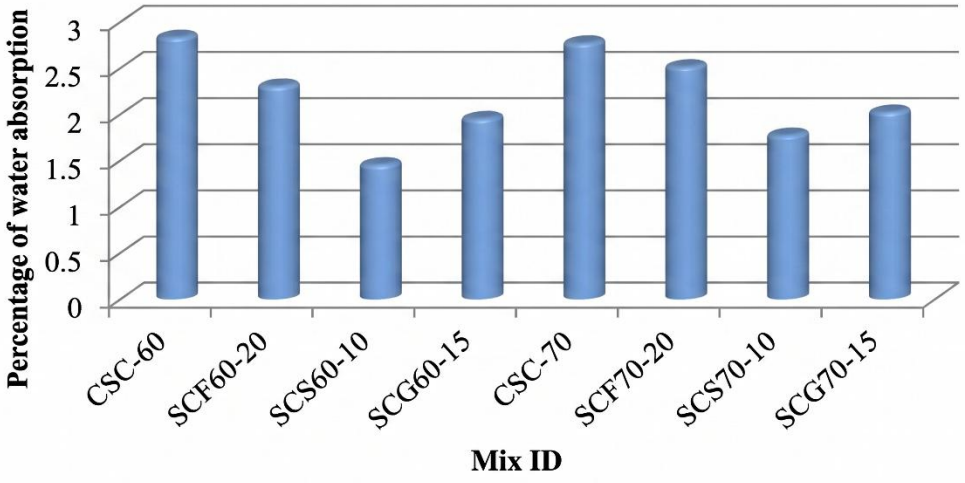

Fig. 8. Water absorption results of HSSCC

5. Limitations and Future Work

Although the findings are promising, certain limitations should be acknowledged:

- Freeze–thaw resistance was not evaluated, which is critical for cold-weather applications.
- Long-term field validation under real service conditions was not conducted; results are based on laboratory-scale exposure tests.
- Dynamic and cyclic loading effects on durability were not studied.

Future work should address these limitations by:

- Conducting freeze–thaw cycle testing in accordance with ASTM C666.
- Implementing field trials in marine and industrial environments.
- Evaluating performance under fatigue, seismic, or impact loading to simulate real structural demands.

6. Conclusions

This study shows that the use of silica fume, fly ash and GGBFS in HSSCC, has a great influence on the durability performance of the material under different stressors of the environment. The results reveal:

- Acid, sulphate and chloride attack tests observations and analysis: The improvement on the concrete quality with silica fume effect has been experienced during the tests of the concrete specimen submitted to the attack of acid, sulphate or chloride over the 90 days. It is full of

silica fume and calcium and it fills the pores in the cement matrix. This concrete building becomes denser and becomes more resistant to environmental pollutants.

- Compressive Strength Results

For M60 Grade:

- Acid Attack: 54.6 MPa (19.82% reduction from normal curing strength)
- Chloride Attack: 61.8 MPa (9.25% reduction from normal curing strength)
- Sulphate Attack: 58.2 MPa (14.54% reduction from normal curing strength)

For M70 Grade:

- Acid Attack: 61.5 MPa (21.56% reduction from normal curing strength)
- Chloride Attack: 70.6 MPa (9.95% reduction from normal curing strength)
- Sulphate Attack: 66.6 MPa (15.05% reduction from normal curing strength)

These values imply that, although reduced, the concrete specimens remain pretty strong, subject to good resilience properties under different environmental conditions. Better performance against any type of exposure is therefore indicated for the lower reduction percentages for chloride attack.

- Effect of Silica fume influences the voids in the concrete have been reduced by the presence of silica fume significantly. The reduction in porosity yields concrete specimens that are more resistant to adverse environmental conditions, and to chemical attack in particular, than other types of concrete specimens.
- Concrete specimens with silica fume and GGBFS mixtures contain very low chloride ion penetration. This performance is better than that of conventional concrete and concrete with fly ash, which demonstrates that the pores of silica fume and GGBFS specimens have been completely filled and improved performance of durability.
- The water absorption test results show that all the specimens conform to ASTM C 140, in water absorption percentage in the specified limits. This result further shows that concrete specimens, especially the silica fume reinforced concrete, has a much lower porosity & with a high quality.
- The incorporation of silica fume in the concrete mix improves density and decreases porosity and thus gives enhanced resistance to acid, sulphate and chloride attacks. Even under these conditions there are some reductions in compressive strength of concrete but overall, the durability of concrete is still high. This further corroborates the use of silica fume & GGBFS to produce high performance concrete as the chloride ion penetration is low & the water absorption standards also follow.

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