Measuring Chloride Levels at Color Change Boundaries to Precisely Determine the Migration Coefficient of Chloride Ion in Concrete composed of Various Cement Types.

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Project Report Approval

The thesis titled " Measuring Chloride Levels at Color Change Boundaries to Precisely Determine the Migration Coefficient of Chloride Ion in Concrete composed of Various Cement Types" submitted by Md. Delwar Hossain (190051205), Tanvir Mustafiz Khan (190051210), Al Shahrier Mohammad Zisan (190051202) has been found satisfactory and accepted as partial fulfillment of the requirement for the degree of Bachelor of Science in Civil Engineering

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Declaration of Candidate

We hereby declare that the undergraduate research work reported in this thesis has been performed by us under the supervision of Assistant Professor Mohammad Zunaied-Bin-Harun and this work has not been submitted elsewhere for any purpose (except for publication).

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Dedication

We dedicate our thesis work to our family. Regardless of whom we would not have been here in the first place.

Also remembering our friends who have been with us through thick and thin and have been a support system we needed whenever we felt down

Lastly would like to dedicate our thesis work to our Thesis mates without whom this work would not have been done. Through many different point of views, agreements and disagreements we stand tall to our testament of creating a better tomorrow and showing the power of being stronger together and being empowered through trust.

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"In the name of Allah, Most Gracious, Most Merciful"

All the praises to Allah (SWT) for giving us the opportunity to complete this book. We wish to express our sincere gratitude to Assistant Professor Mohammad Zunaied-Bin-Harun, for providing us with all the necessary facilities, giving undivided attention and fostering us all the way through the research. His useful comments, remarks and engagement helped us with the learning process throughout the thesis.

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We also place on record, our sense of gratitude to one and all, who directly or indirectly, have contributed to this venture

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Chapter 1: Introduction

1.1 Background

Concrete is a critical material in modern construction, known for its versatility, strength, and relatively low production cost. Despite its robustness, concrete structures face challenges when exposed to aggressive environments, particularly chloride-laden settings, such as marine areas and regions that use de-icing salts. Chloride ingress in concrete leads to the corrosion of embedded steel reinforcement, one of the primary causes of structural deterioration. This corrosion compromises the integrity of the concrete and significantly reduces its service life, creating a pressing need for maintenance, repairs, or replacement, all of which incur substantial costs and environmental impact.

1.2 Life Cycle Analysis (LCA) and the Importance of Durability

A life cycle analysis (LCA) of concrete structures highlights the environmental and economic benefits of enhancing durability. The life cycle stages of concrete include material extraction, production, construction, operation, maintenance, and end-of-life phases, each contributing to the overall environmental footprint. The operational and maintenance phases, often spanning decades, are particularly susceptible to the effects of chloride-induced deterioration, which can lead to costly repairs or premature replacements. These repairs require additional materials, energy, and labor, further increasing the carbon footprint associated with the concrete structure.

Improving chloride resistance in concrete reduces the frequency and severity of these interventions, thereby extending the structure’s life cycle. A durable concrete mix not only minimizes the environmental impact by lowering resource use but also leads to significant cost savings over the structure's lifetime. Consequently, understanding and enhancing the resistance of concrete to chloride ingress is vital for creating sustainable infrastructure solutions.

1.3 Research Objectives

This research aims to investigate the effects of various cementitious compositions on the chloride resistance of concrete. Specifically, the objectives are to:

1. Analyze the chloride migration and diffusion behavior of concrete made with different cement types, including blends with supplementary cementitious materials (SCMs) like slag and fly ash.
2. Evaluate the effectiveness of these mixes in resisting chloride penetration by employing standard durability tests such as Ultrasonic Pulse Velocity (UPV), Compressive Strength, Rapid Chloride Penetration Test (RCPT), and Chloride Migration Tests.
3. Provide insights into optimal cement compositions that enhance the long-term durability of concrete structures exposed to chloride environments.

1.4 Research Significance

The findings from this research hold potential implications for both industry practitioners and environmental policymakers. Enhanced durability translates into lower maintenance and repair requirements, conserving resources and reducing emissions associated with construction activities. By understanding which cementitious mixes offer superior chloride resistance, this study aims to support the development of concrete that is both cost-effective and environmentally sustainable.

This research will serve as a valuable reference for the construction industry, providing guidelines for selecting cement types that improve concrete's life cycle performance, particularly in aggressive chloride environments.

1.5 Structure of the Thesis

This thesis is organized into the following chapters:

1. **Chapter 2: Literature Review** - An examination of existing research on chloride penetration, the role of supplementary cementitious materials, and commonly used testing methods for durability assessment.
2. **Chapter 3: Methodology** - A detailed description of the experimental setup, including sample preparation, testing protocols, and analysis techniques.
3. **Chapter 4: Results and Analysis** - Presentation and interpretation of data collected from UPV, compressive strength, chloride profiling, and titration tests.
4. **Chapter 5: Discussion** - Analysis of findings with respect to different cement mixes and their implications for durability and life cycle.
5. **Chapter 6: Conclusion and Recommendations** - Summary of key findings and practical recommendations for industry applications and future research directions.

Chapter 2: Literature Review

2.1 Chloride Penetration in Concrete

Chloride ingress is a major cause of concrete deterioration, particularly in structures exposed to marine environments or de-icing salts. When chlorides penetrate the concrete matrix, they reach the steel reinforcement, disrupting the passive layer that protects it from corrosion. This process initiates corrosion, leading to expansion and cracking within the concrete, thereby compromising structural integrity.

Chloride transport in concrete occurs primarily through diffusion, capillary absorption, and ionic migration. Diffusion is the most significant mechanism in saturated concrete, where ions move from areas of high concentration (such as external sources of chloride) to low concentration within the concrete. Various factors influence the rate and depth of chloride penetration, including the water-to-cement ratio, porosity, and permeability of the concrete matrix. Studies show that reducing the porosity and increasing the density of concrete through mix design improvements can significantly enhance chloride resistance.

2.2 Effects of Supplementary Cementitious Materials (SCMs)

Supplementary Cementitious Materials (SCMs), such as slag and fly ash, are often incorporated into concrete to improve its durability and resistance to chloride ingress. SCMs contribute to the formation of a denser microstructure, which reduces porosity and enhances the concrete's ability to resist chloride ions. SCMs also react with calcium hydroxide, produced during the hydration of Portland cement, to form additional calcium silicate hydrate (C-S-H) gel, which further refines the pore structure.

1. **Slag**: Ground granulated blast-furnace slag (GGBFS) is a byproduct of steel production and has pozzolanic and latent hydraulic properties that make it highly beneficial as a cement replacement. Research indicates that replacing a portion of ordinary Portland cement (OPC) with slag improves chloride resistance by densifying the microstructure and reducing the availability of free calcium hydroxide for chloride binding. Studies have shown that incorporating 35-65% slag into concrete can significantly reduce chloride ion diffusion.

2. **Fly Ash**: Fly ash, a byproduct of coal combustion, is another widely used SCM. It has pozzolanic properties, which means it reacts with calcium hydroxide to produce additional C-S-H, thus refining the pore structure of concrete. Fly ash is typically used at replacement levels of 15-50%. Research demonstrates that fly ash improves chloride resistance, although its effectiveness can depend on the type and fineness of the ash used. Fly ash-blended concrete exhibits lower permeability and improved durability due to the refined pore structure.

The use of SCMs not only improves chloride resistance but also reduces the carbon footprint of concrete by lowering the demand for Portland cement, which is energy-intensive to produce. Thus, incorporating SCMs aligns with sustainable construction practices and enhances the life cycle of concrete structures.

2.3 Test Methods for Evaluating Chloride Migration and Durability

To assess the chloride resistance of concrete, various testing methods are employed, each with specific standards and procedures. The most common tests include the Rapid Chloride Penetration Test (RCPT), Chloride Migration Test, Ultrasonic Pulse Velocity (UPV) testing, and Compressive Strength testing. Each test provides insights into different aspects of concrete's durability and resistance to chloride ingress.

1. **Rapid Chloride Penetration Test (RCPT)**: The RCPT, as outlined in **ASTM C1202**, measures the electrical charge passed through a concrete sample over a 6-hour period while applying a 60V potential across the sample. This test is an indirect measure of concrete's permeability to chloride ions. Higher charge values indicate higher permeability and thus lower resistance to chloride ingress. Although the RCPT is widely used due to its simplicity, it has some limitations, including susceptibility to temperature effects and the presence of other ions that may affect the current flow.

2. **Chloride Migration Test (NT Build 492)**: This non-steady-state migration test involves applying an electrical field across a concrete sample to accelerate the movement of chloride ions. After the test, the sample is split open, and a silver nitrate solution is sprayed to visualize the depth of chloride penetration. The migration coefficient calculated from this test is more directly related to chloride transport and provides a more accurate assessment of concrete's resistance to chloride ingress than RCPT.

3. **Ultrasonic Pulse Velocity (UPV)**: UPV testing, in accordance with **ASTM C597**, is a non-destructive test method that measures the velocity of an ultrasonic pulse passing through a concrete sample. Higher pulse velocities indicate a denser, less porous concrete matrix, which correlates with improved durability and resistance to chloride ingress. UPV testing is useful for assessing the quality and uniformity of concrete and for detecting internal flaws that may affect chloride resistance.

4. **Compressive Strength Testing**: Compressive strength is a fundamental property that reflects the quality and durability of concrete. Testing compressive strength, as per **ASTM C39**, involves applying a uniaxial load to a cylindrical sample until failure. Higher compressive strength often correlates with a denser matrix and better resistance to chloride penetration. It is a key indicator of concrete's durability and overall quality.

2.4 Previous Studies on Chloride Ingress and Durability

Several studies have explored the effectiveness of various cementitious compositions in enhancing the chloride resistance of concrete. For instance, studies have shown that concrete mixes with higher slag and fly ash content generally exhibit lower chloride permeability, due to the refined pore structure and densification imparted by these SCMs.

In a study by Maes et al. (2012), it was demonstrated that a 50% replacement of OPC with slag reduced the chloride diffusion coefficient by 66%, indicating substantial improvement in chloride resistance. Similarly, research by Elfmarkova et al. (2015) found that concrete containing high fly ash content performed comparably to slag-blended concrete, particularly in terms of reducing chloride diffusion and migration coefficients.

Additionally, the use of non-destructive testing methods, such as UPV, has become increasingly popular for evaluating the internal quality and durability of concrete in situ. These studies highlight the importance of selecting appropriate test methods to accurately measure chloride resistance, as well as the value of using SCMs to enhance durability and sustainability.

2.5 Summary

The literature indicates that chloride ingress is a significant factor in the deterioration of concrete structures, especially in aggressive environments. SCMs, such as slag and fly ash, have been shown to be effective in improving concrete's durability and resistance to chloride ions. Moreover, employing standardized tests like RCPT, NT Build 492, UPV, and compressive strength testing provides a comprehensive understanding of concrete's durability properties.

This research builds on these foundations by examining the performance of various cement types and SCM combinations through a series of standardized tests, ultimately contributing to the development of concrete mixes with enhanced life cycles and sustainability.

Chapter 3: Methodology

This chapter outlines the methodology used to investigate the chloride migration and durability properties of various concrete mixes incorporating supplementary cementitious materials (SCMs) such as slag and fly ash. The testing procedures followed established ASTM and NT Build standards, and each step was designed to provide insights into the chloride resistance, mechanical strength, and durability of the concrete samples.

3.1 Sample Preparation and Casting

Concrete samples were prepared based on the specifications detailed in **Thesis Defence_Main**. The concrete mixes were designed with different proportions of Ordinary Portland Cement (OPC) blended with SCMs, specifically slag and fly ash, to assess their influence on chloride resistance and durability. The mix compositions included:

- **Case 1 (OPC)**: 100% Ordinary Portland Cement
- **Case 2 (OPC + Slag 35%)**: 65% OPC, 35% Slag
- **Case 3 (OPC + Slag 50%)**: 50% OPC, 50% Slag
- **Case 4 (OPC + Slag 65%)**: 35% OPC, 65% Slag
- **Case 5 (OPC + Fly Ash 35%)**: 65% OPC, 35% Fly Ash
- **Case 6 (OPC + Fly Ash 50%)**: 50% OPC, 50% Fly Ash
- **Case 7 (OPC + Fly Ash 65%)**: 35% OPC, 65% Fly Ash

- **Case 8 (PCC)**: 100% Portland Composite Cement

Type of Cement	Wc	Wca	Wfa	Ww	Wslag	Wfly	Vslag	Vfly	Vc	Vca	Vfa	Vw	Vv
CEM Type I 100%	450	951	692	225	0	0	0	0	0.142857143	0.345818182	0.2703125	0.225	0.02
CEM Type II A-M	450	923	672	225	0	0	0	0	0.160714286	0.335636364	0.2625	0.225	0.02
CEM Type I 65% + Slag 35%	342	951	692	225	108	0	0.05	0	0.108571429	0.345818182	0.2703125	0.225	0.02
CEM Type I 50% + Slag 50%	295.7142857	951	692	225	154.2857143	0	0.071428571	0	0.093877551	0.345818182	0.2703125	0.225	0.02
CEM Type I 35% + Slag 65%	249.4285714	951	692	225	200.5714286	0	0.092857143	0	0.079183673	0.345818182	0.2703125	0.225	0.02
CEM Type I 65% + Fly Ash 35%	362	951	692	225	0	88	0	0.05	0.114920635	0.345818182	0.2703125	0.225	0.02
CEM Type I 50% + Fly Ash 50%	324.2857143	951	692	225	0	125.7142857	0	0.071428571	0.102947846	0.345818182	0.2703125	0.225	0.02
CEM Type I 35% + Fly Ash 65%	286.5714286	951	692	225	0	163.4285714	0	0.092857143	0.090975057	0.345818182	0.2703125	0.225	0.02

Fig: Concrete Mix Design

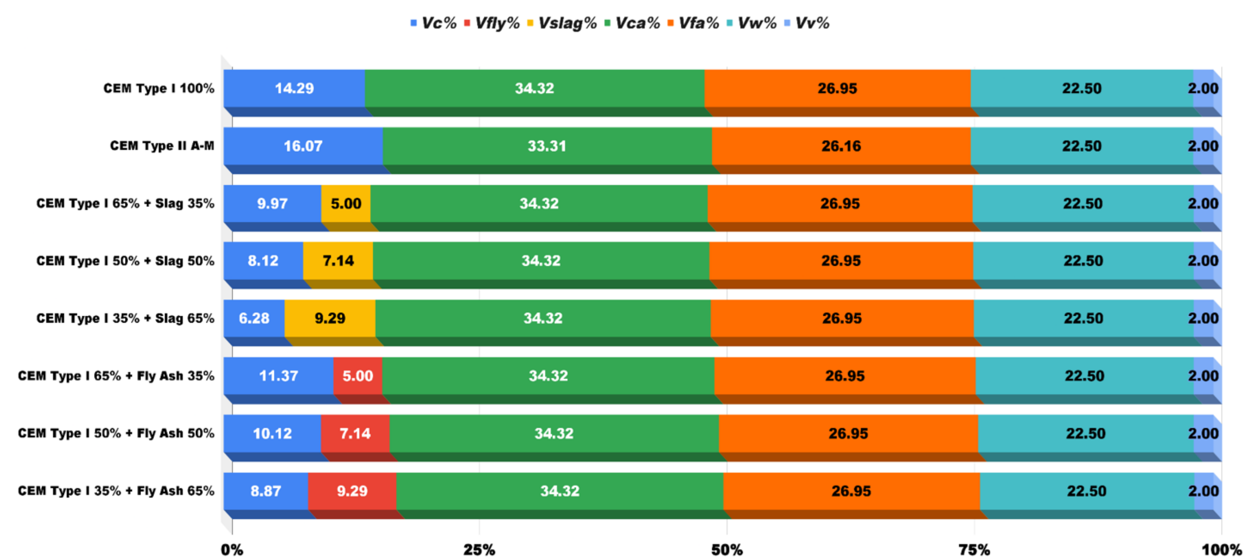

Fig: Bar diagram of Concrete Mix Design

The following parameters were kept constant for all mixes:

- **Water-to-cement (W/C) ratio**: 0.5
- **Maximum aggregate size (MAS)**: 19mm
- **Sand-to-aggregate (S/A) ratio**: 0.44

Each mix was thoroughly blended, and cylindrical samples were cast using standard molds. A total of **128 cylindrical specimens** were prepared (16 specimens for each mix) to ensure sufficient replicates for testing across different time intervals (7, 14, and 28 days). The specimens were demolded after 24 hours and then cured in a water tank at a controlled temperature of 20°C until testing.

3.2 Testing Procedures

To evaluate the properties of each concrete mix, a series of tests were conducted, including Ultrasonic Pulse Velocity (UPV), Compressive Strength, Rapid Chloride Penetration Test (RCPT), Chloride Migration Test, and Chloride Profiling. The details of each test are described below.

3.2.1 Strength Testing and Ultrasonic Pulse Velocity (UPV) Measurements

Compressive Strength Testing
The compressive strength of the concrete specimens was measured at 7, 14, and 28 days in accordance with **ASTM C39**. Compressive strength testing was conducted by placing each cylindrical specimen in a compressive testing machine, where a uniaxial load was gradually applied until the specimen failed. The maximum load was recorded, and the compressive strength (MPa) was calculated.

Ultrasonic Pulse Velocity (UPV) Testing
UPV testing was conducted to assess the internal quality and homogeneity of the concrete samples at each curing interval. UPV measurements were performed following **ASTM C597**, which involves transmitting ultrasonic pulses through the specimen. The velocity of these pulses is related to the density and integrity of the concrete—higher velocities indicate a more compact matrix with fewer voids. UPV values were recorded at 7, 14, and 28 days, providing additional insight into how each mix performed in terms of structural integrity.

Data Collected:

- Compressive Strength (MPa) and UPV (m/s) values at 7, 14, and 28 days for each case.
- **Graphs**: UPV vs. Days and Compressive Strength vs. Days for each mix.

3.2.2 Rapid Chloride Penetration Test (RCPT)

The **Rapid Chloride Penetration Test (RCPT)** was performed according to **ASTM C1202**. This test assesses concrete permeability by measuring the electrical charge passed through the specimen over a 6-hour period. The following procedure was followed:

1. **Preparation**: A 50mm thick slice was cut from each cylindrical sample, ensuring flat and smooth surfaces for accurate testing.
2. **Setup**: The specimen was placed between two cells—one filled with a sodium chloride (NaCl) solution and the other with sodium hydroxide (NaOH).
3. **Voltage Application**: A 60V potential difference was applied across the sample for 6 hours, during which the total electrical charge passed (in coulombs) was recorded.

The RCPT provides an indirect measurement of the concrete's permeability to chloride ions. Higher charge values indicate higher permeability, suggesting lower resistance to chloride ingress.

Data Collected:

- **Coulomb values** indicating chloride permeability for each mix.
- **Graphs**: Charge Passed (Coulombs) vs. Cement Mix Type.

3.2.3 Chloride Migration Test (NT Build 492)

The **Chloride Migration Test** was conducted using the **NT Build 492** method. This non-steady-state migration test measures the depth of chloride penetration under an externally applied electrical field. The procedure was as follows:

1. **Specimen Preparation**: Cylindrical samples were cut into 50mm thick slices.
2. **Testing Setup**: Each slice was placed between two chambers, one containing NaCl solution and the other containing an alkaline solution.

3. **Voltage Application**: A DC voltage of 30V to 60V was applied across the specimen to accelerate chloride ion migration.
4. **Depth Measurement**: After the test, the specimens were split open, and a silver nitrate (AgNO3) solution was sprayed on the split surface. The depth of the white precipitate formed by silver chloride was measured, representing the chloride penetration depth.

The chloride migration coefficient was calculated based on the voltage applied, duration of exposure, and depth of chloride penetration. This coefficient provides a direct measure of the concrete's resistance to chloride migration.

Data Collected:

- Chloride Migration Coefficients for each mix.
- **Graphs**: Migration Depth vs. Cement Mix Type.

3.2.4 Chloride Profiling and Titration for Chloride Concentration

To determine the chloride concentration at various depths, **chloride profiling** was conducted on each specimen after the migration test.

1. **Sampling**: Concrete samples were sliced at specific depths to analyze the chloride concentration at each level.
2. **Preparation**: Each sliced segment was crushed into a fine powder and mixed with deionized water in a 1:1 ratio to create a solution.
3. **Conditioning**: The solution was conditioned in an oven to ensure consistency before chemical analysis.
4. **Titration**: Using volumetric titration, the chloride concentration in each sample was measured. The results provided a detailed chloride concentration profile for each mix.

This profiling method allowed for precise measurements of chloride content at different depths, giving a comprehensive view of chloride penetration and validating the migration and permeability results obtained from RCPT and NT Build 492.

Data Collected:

- Chloride Concentration (mg/L) at various depths for each mix.
- **Graphs**: Chloride Concentration vs. Depth for each case.

3.3 Data Analysis

The data collected from the various tests were analyzed statistically to understand the performance differences among the cement mixes. Graphs were generated to visualize trends in UPV, compressive strength, chloride migration, and concentration profiles. Statistical analysis helped confirm the reliability of the results and provided insights into the significance of each cement composition's performance.

Chapter 4: Results and Analysis

This chapter summarizes and interprets the results from the tests conducted on concrete samples with different cement compositions. The focus is on understanding how supplementary cementitious materials (SCMs), such as slag and fly ash, influence the properties of concrete, particularly its resistance to chloride ingress, strength development, and internal structure.

4.1 Strength Testing and Ultrasonic Pulse Velocity (UPV) Results

4.1.1 Compressive Strength Results

Compressive strength was measured at 7, 14, and 28 days to evaluate the strength development of each mix. The results indicate that concrete mixes with higher SCM content generally displayed a slower rate of strength gain, as SCMs like slag and fly ash contribute to a more gradual hydration process. However, the final strength values at 28 days for these mixes were often comparable or even superior to mixes with only OPC.

- **OPC (Case 1)** exhibited a rapid early strength gain, reaching a compressive strength of 46.34 MPa at 28 days.
- **OPC + Slag 35% (Case 2)** showed higher strength at 28 days (53.67 MPa) compared to OPC, demonstrating the positive effect of slag in increasing ultimate strength.
- **Higher Slag Content (Cases 3 and 4)** resulted in lower early strength but adequate long-term strength, with Case 3 achieving 38.27 MPa at 28 days.
- **OPC + Fly Ash Mixes (Cases 5 to 7)** exhibited intermediate strength development, with Case 5 reaching 45.27 MPa at 28 days.

Graphical Analysis: A line graph of **Compressive Strength vs. Time** (7, 14, and 28 days) will be included, comparing each mix. This will highlight the slower strength development in mixes with higher SCM content.

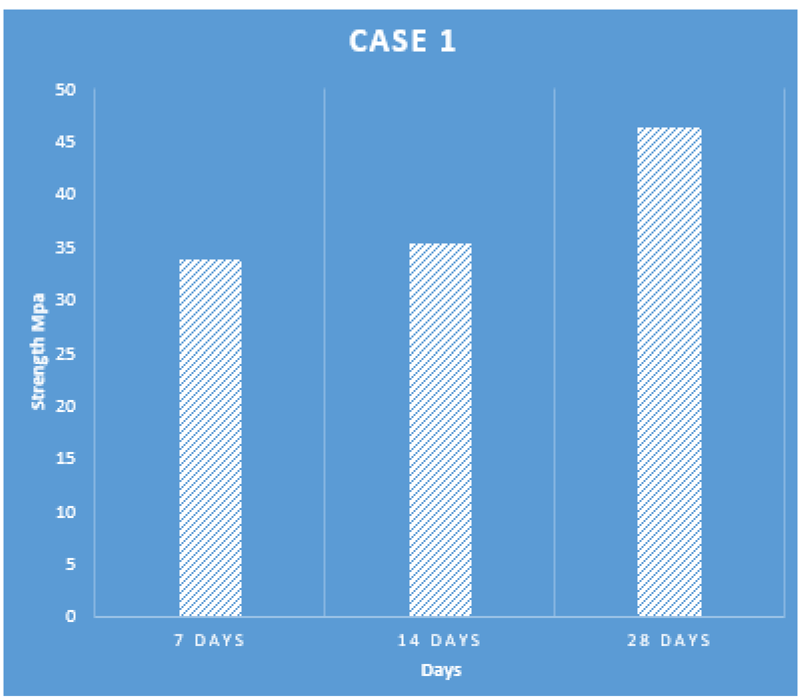

Fig: Case 1 Compressive Strength

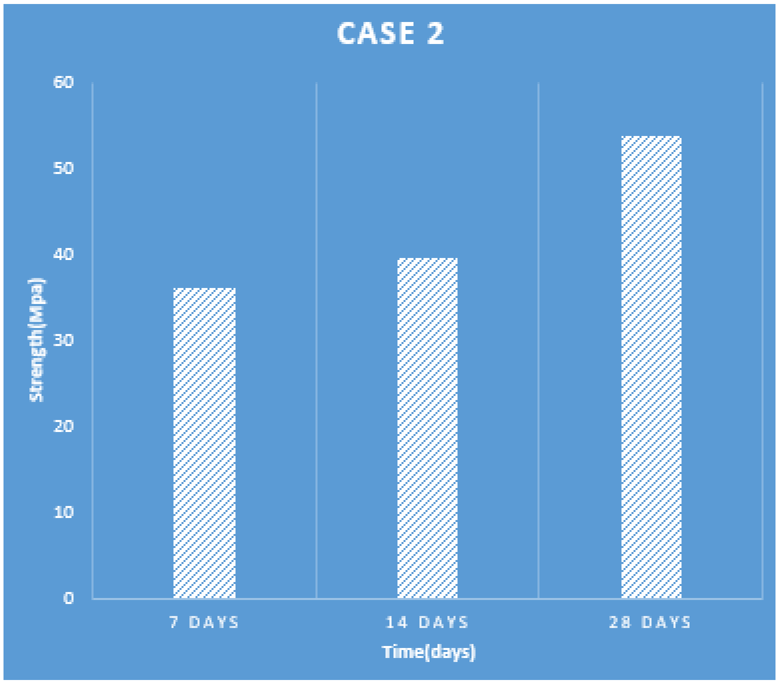

Fig: Case 2 Compressive Strength

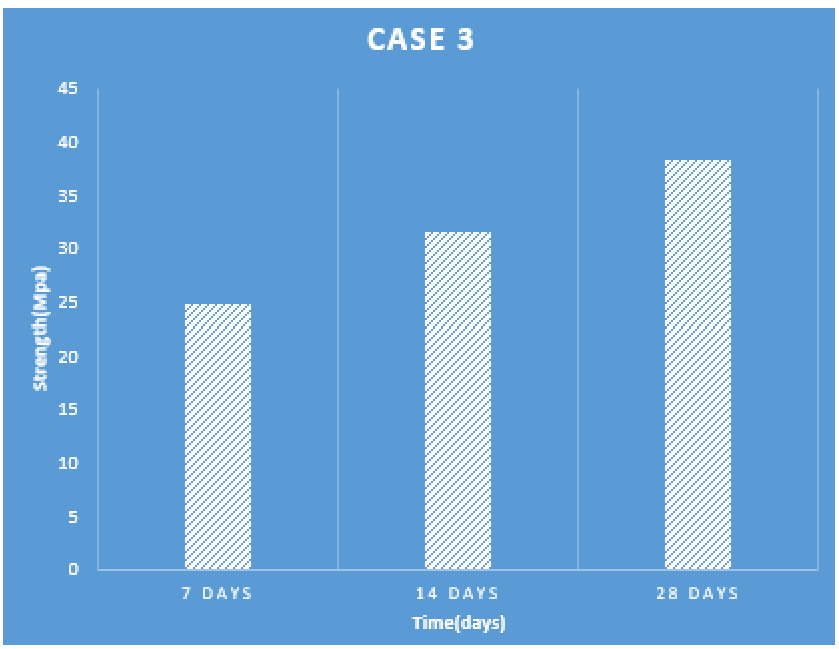

Fig: Case 3 Compressive Strength

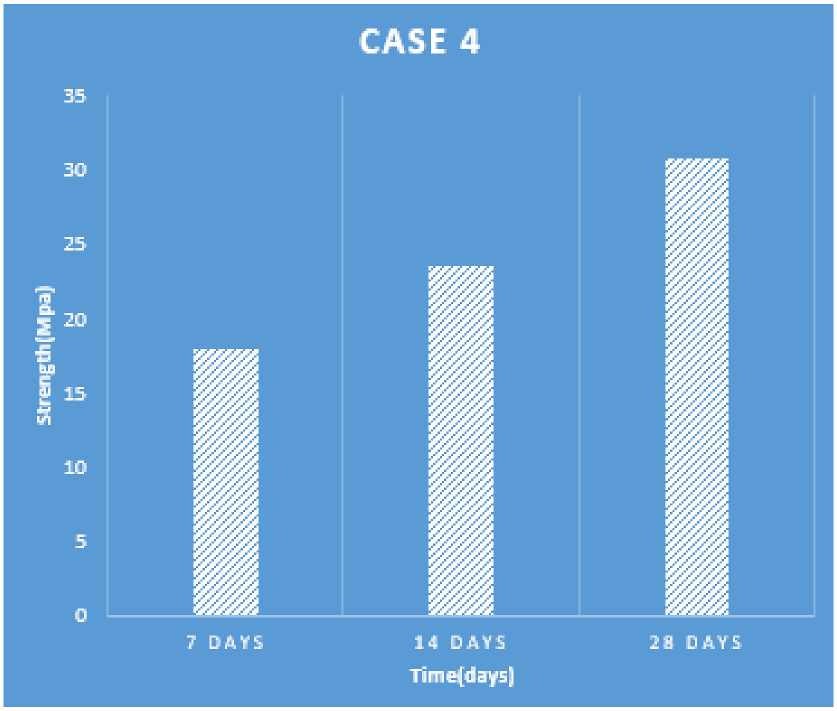

Fig: Case 4 Compressive Strength

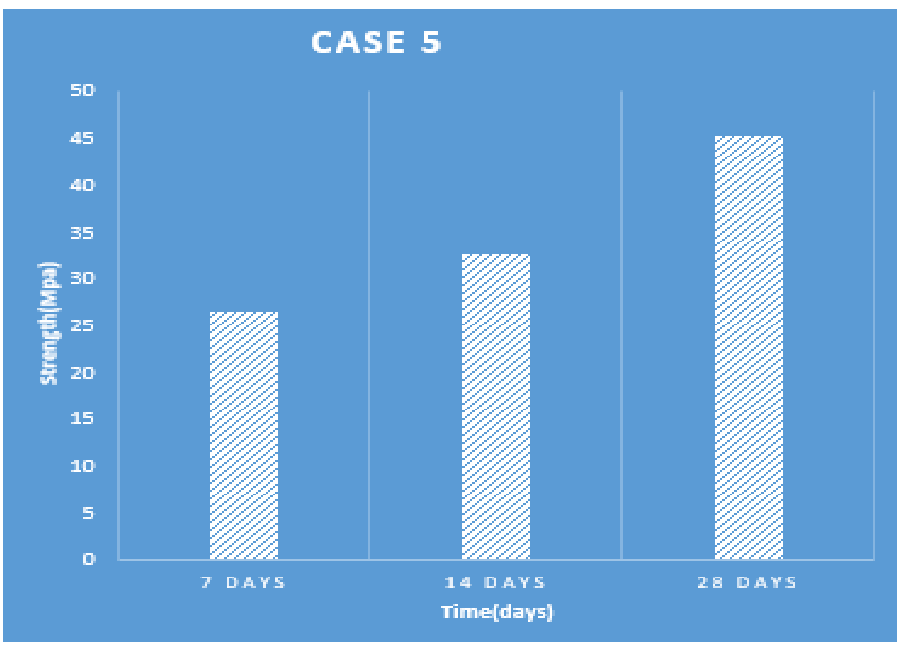

Fig: Case 5 Compressive Strength

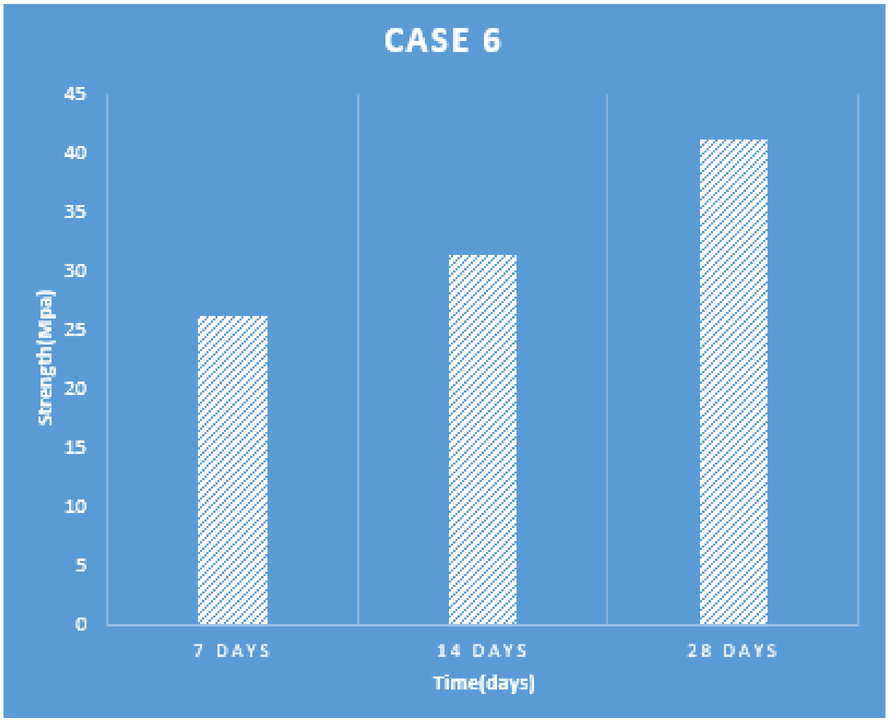

Fig: Case 6 Compressive Strength

4.1.2 Ultrasonic Pulse Velocity (UPV) Results

UPV testing was conducted in parallel with strength tests to assess the internal quality and density of the concrete mixes. Higher UPV values generally correspond to a denser, more homogenous concrete matrix, which is an indicator of better durability.

- **OPC (Case 1)** had the highest UPV values throughout, indicating a dense and uniform matrix.
- **OPC + Slag Mixes** exhibited slightly lower UPV values, suggesting a more gradual densification of the matrix over time due to the slower hydration of slag.
- **OPC + Fly Ash Mixes** showed a moderate increase in UPV, with Case 5 reaching comparable values to the OPC mix by 28 days.

Graphical Analysis: A line graph of **UPV vs. Time** for each case will show how UPV values increase over time, reflecting the gradual densification of SCM-containing mixes.

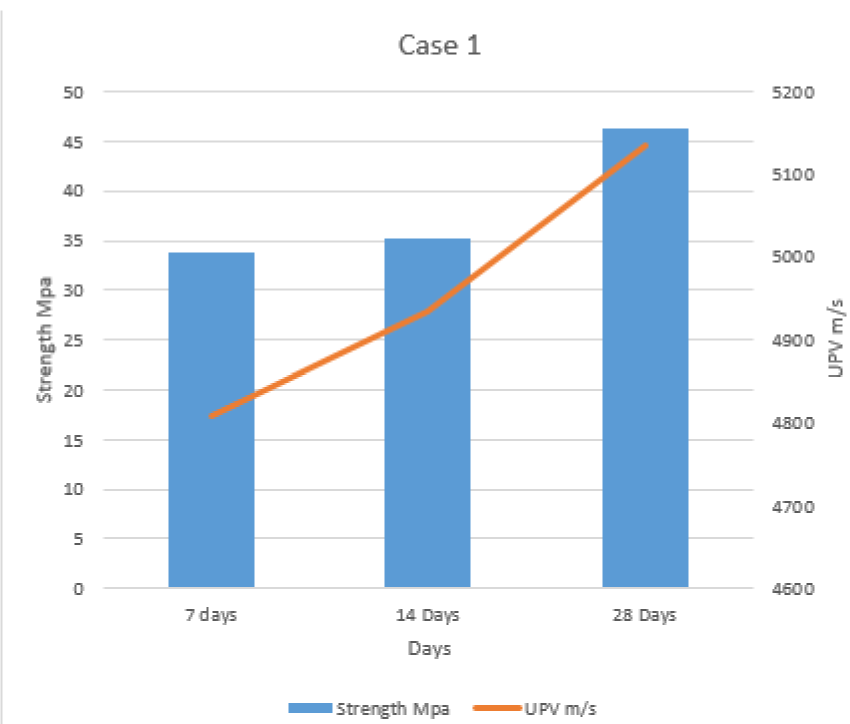

Fig: Case 1 UPV

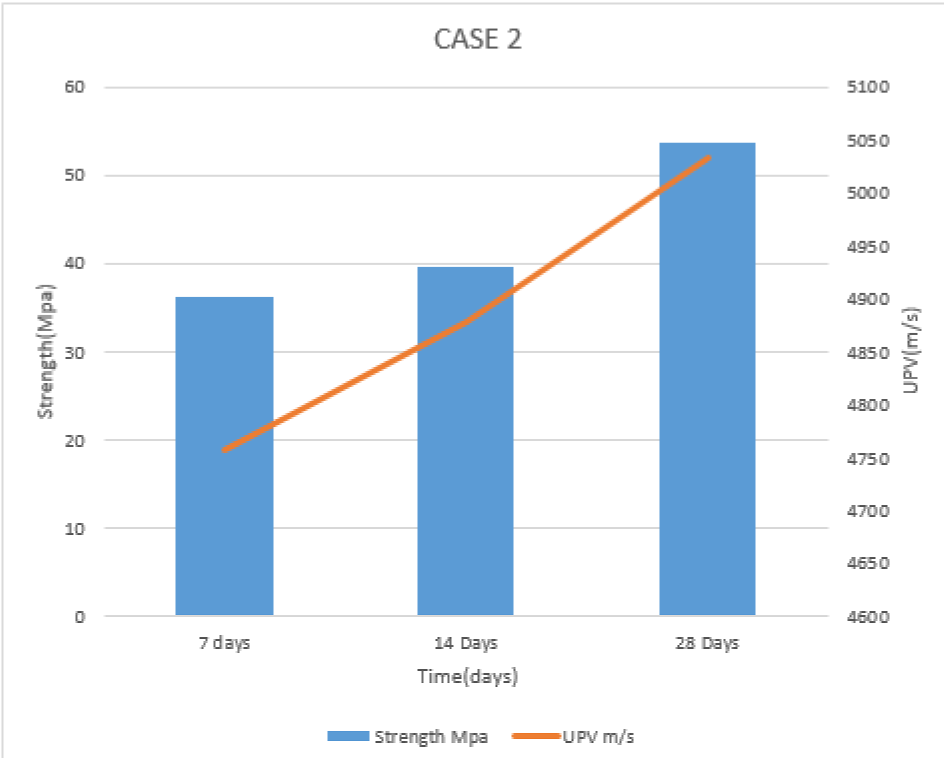

Fig: Case 2 UPV

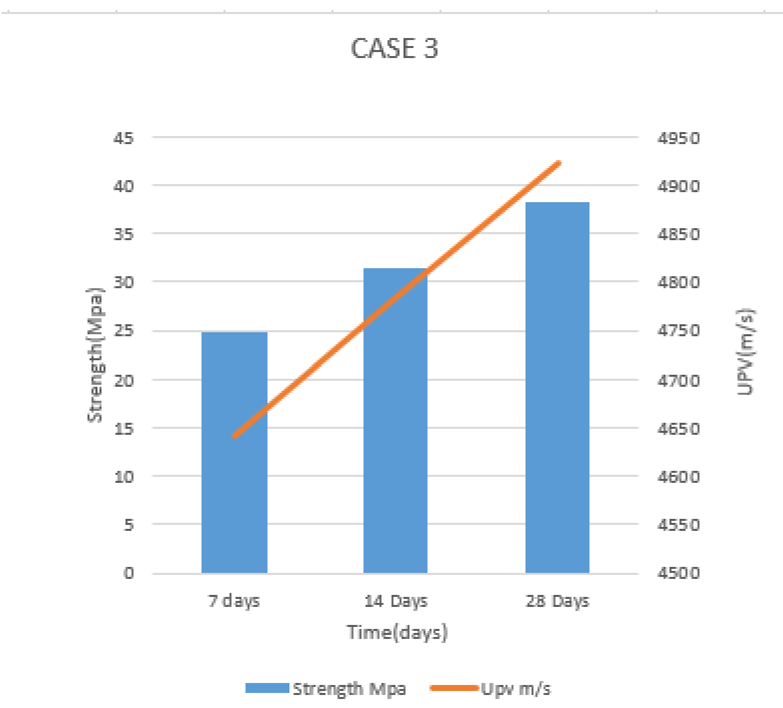

Fig: Case 3 UPV

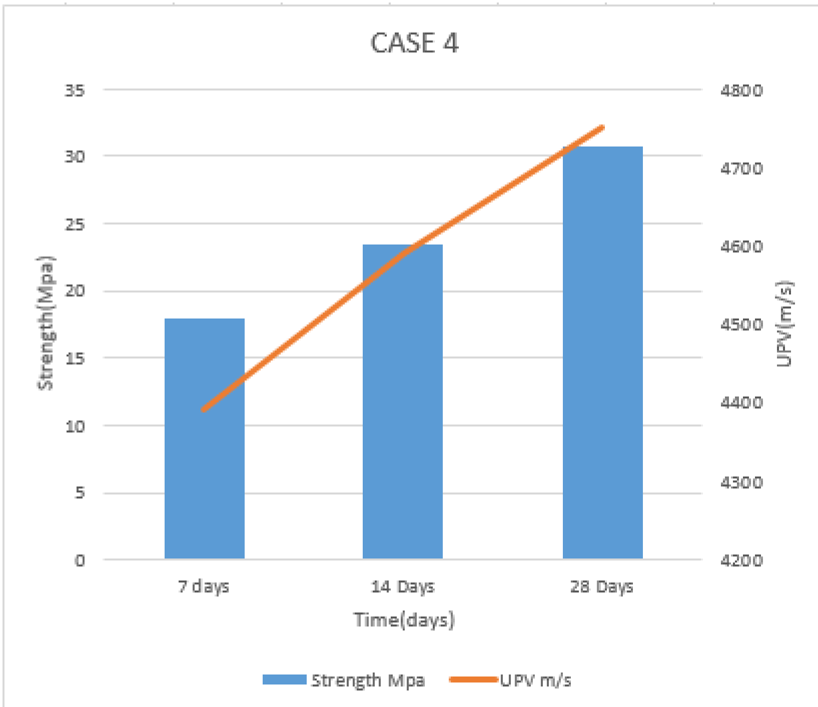

Fig: Case 4 UPV

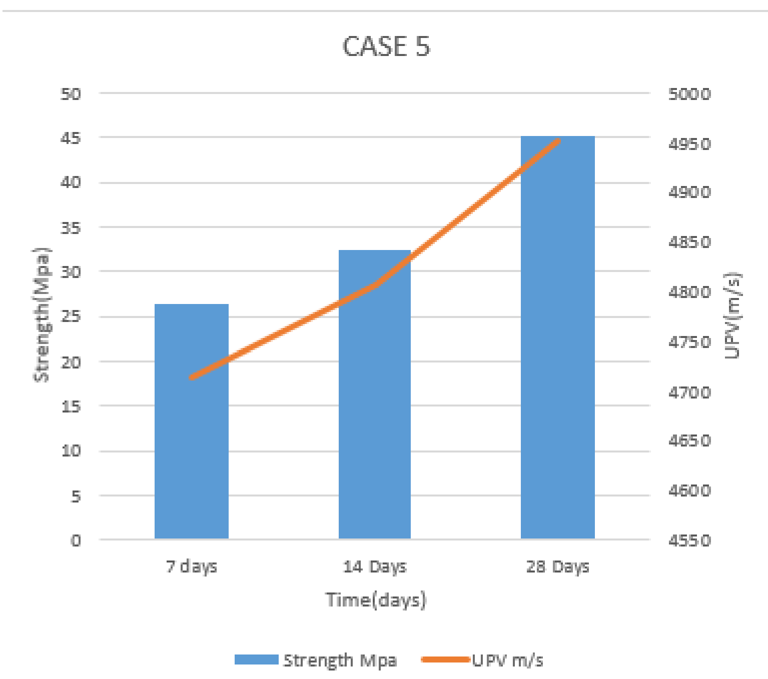

Fig: Case 5 UPV

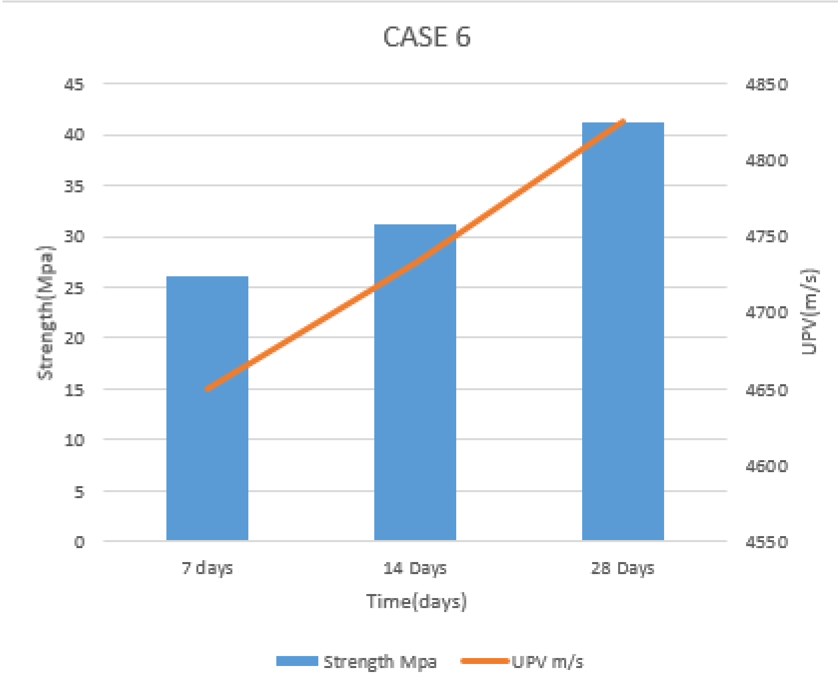

Fig: Case 6 UPV

4.2 Rapid Chloride Penetration Test (RCPT) Results

The RCPT results, measured in coulombs, provide insight into the permeability of each concrete mix to chloride ions. Lower coulomb values indicate lower permeability and, thus, greater resistance to chloride ingress.

- **OPC (Case 1)** recorded the highest charge passed (6039 coulombs), indicating the lowest resistance to chloride ingress.
- **OPC + Slag 35% (Case 2)** and **OPC + Slag 50% (Case 3)** exhibited much lower charge values, 3762.9 and 1503 coulombs, respectively, showcasing significant improvements in chloride resistance with increasing slag content.
- **OPC + Slag 65% (Case 4)** recorded the lowest charge (600.3 coulombs), indicating exceptional resistance to chloride penetration.
- **Fly Ash Mixes (Cases 5 to 7)** showed intermediate values, with Case 5 achieving 1034.1 coulombs, indicating moderate improvement in chloride resistance compared to OPC.
- **Graphical Analysis**: A bar chart of **Coulombs Passed vs. Cement Mix Type** will compare the permeability of each mix, emphasizing the substantial reduction in permeability achieved by higher slag content.

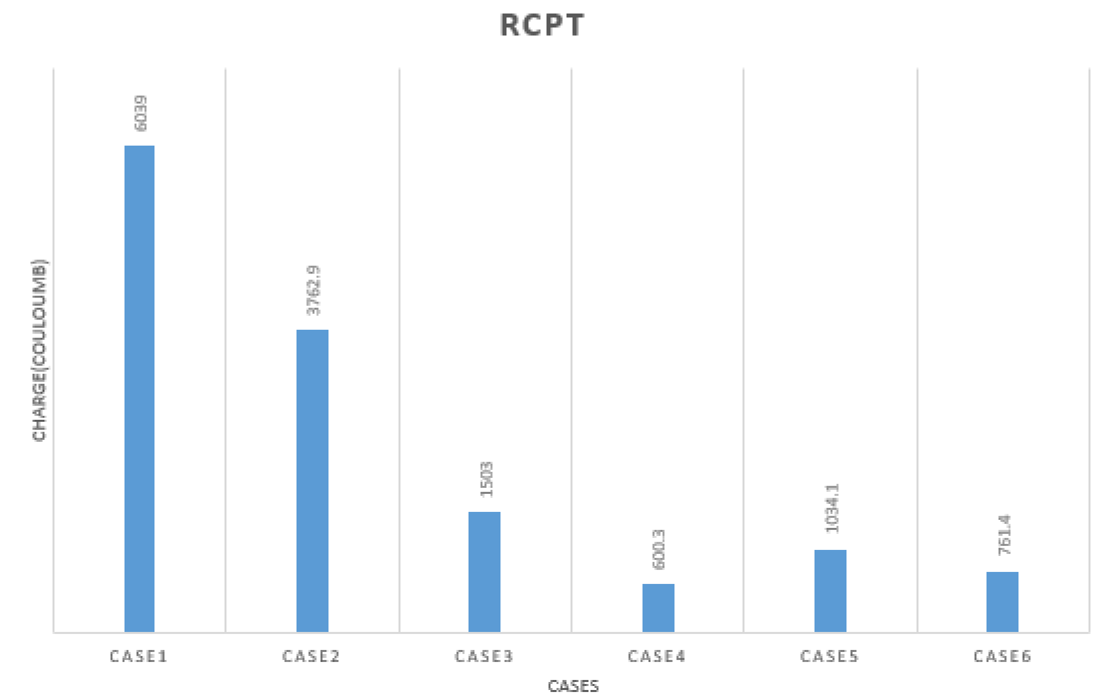

Fig: Coulomb Value of all Specimens

4.3 Chloride Migration Test Results

The chloride migration test provides a direct measure of the chloride migration coefficient for each concrete mix, indicating the rate at which chloride ions can penetrate under an electric field.

- **OPC (Case 1)** exhibited the highest migration coefficient, reinforcing the RCPT findings of higher permeability.
- **OPC + Slag Mixes** showed a notable decrease in migration coefficients, with **OPC + Slag 65%** displaying the lowest coefficient, indicating strong resistance to chloride migration.
- **Fly Ash Mixes** demonstrated moderate resistance, with **OPC + Fly Ash 35% (Case 5)** performing better than the higher fly ash content mixes.

Graphical Analysis: A bar chart of **Migration Coefficient vs. Cement Mix Type** will illustrate the reduced chloride migration coefficients for SCM-containing mixes, especially those with higher slag content.

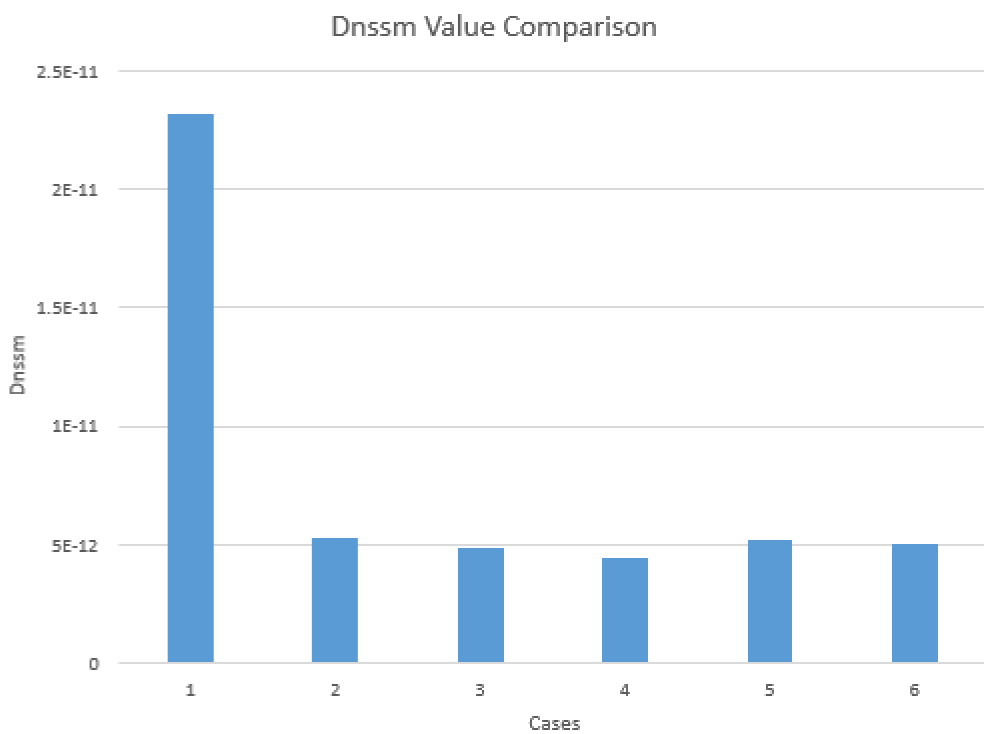

Fig: Migration Coefficient Comparison

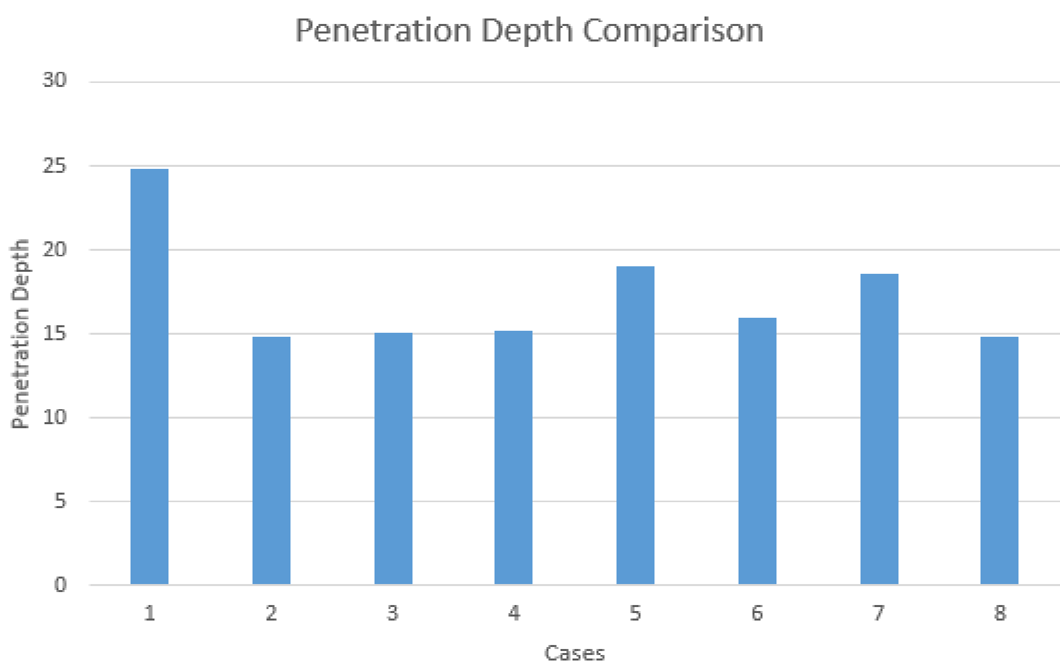

Fig: Penetration Depth Comparison

4.4 Chloride Profiling and Titration Results

Chloride profiling was conducted by slicing the samples at various depths after the migration test and measuring chloride concentration through titration. This profiling provides detailed insights into how deeply chloride ions penetrated within each concrete mix.

- **OPC (Case 1)** showed higher chloride concentrations at deeper depths, indicating a higher penetration rate.
- **OPC + Slag Mixes** demonstrated significantly lower chloride concentrations at the same depths, with **OPC + Slag 65%** having the shallowest chloride penetration, indicating the best performance in resisting chloride ingress.
- **Fly Ash Mixes** showed intermediate results, with **OPC + Fly Ash 35%** performing relatively well compared to OPC.

Graphical Analysis: Line graphs of **Chloride Concentration (mg/L) vs. Depth** for each case will illustrate the penetration depth, highlighting the superior performance of slag-containing mixes in preventing chloride ingress. A detailed chart showcasing all the titration data is provided below:

Case	Initial Agno3,mL		Final Agno3,mL		Final result(mg/L)		result for 1ml sample(result/1000)	
	Yellow	Black	Yellow	Black	Yellow	Black	Yellow	Black
OPC	18	18.7	18.7	21.7	250	1400	0.25	1.4
OPC + slag 35	6	18.4	6.8	22.4	300.3	1902.05	0.3003	1.90205
OPC + slag 50	22.3	22.9	22.8	24.9	150	900	0.15	0.9
OPC + slag 65	18.3	20.1	19.9	22.2	700	951	0.7	0.951
OPC + FA 35	15.2	16.1	16.1	18.2	350	951	0.35	0.951
OPC + FA 50	7	7.9	7.9	9	350	450	0.35	0.45
OPC + FA 65	9.1	10.2	10.1	11.8	400	700	0.4	0.7
PCC	11.9	13.2	13.1	15.2	500	900	0.5	0.9

This chart shows the detailed data of the titration results that were conducted on the crushed concrete specimens. Titration samples were prepared in 1:1 ratio and conditioned in the oven to reach 60^{o}C temperature.

4.5 Summary of Results

The results from strength testing, UPV, RCPT, chloride migration, and chloride profiling collectively indicate that SCMs, particularly slag, play a significant role in enhancing the chloride resistance of concrete. The key findings are as follows:

- **Compressive Strength**: Slag and fly ash mixes displayed slower early strength gain but achieved comparable or higher strength at 28 days, particularly for OPC + Slag 35%.

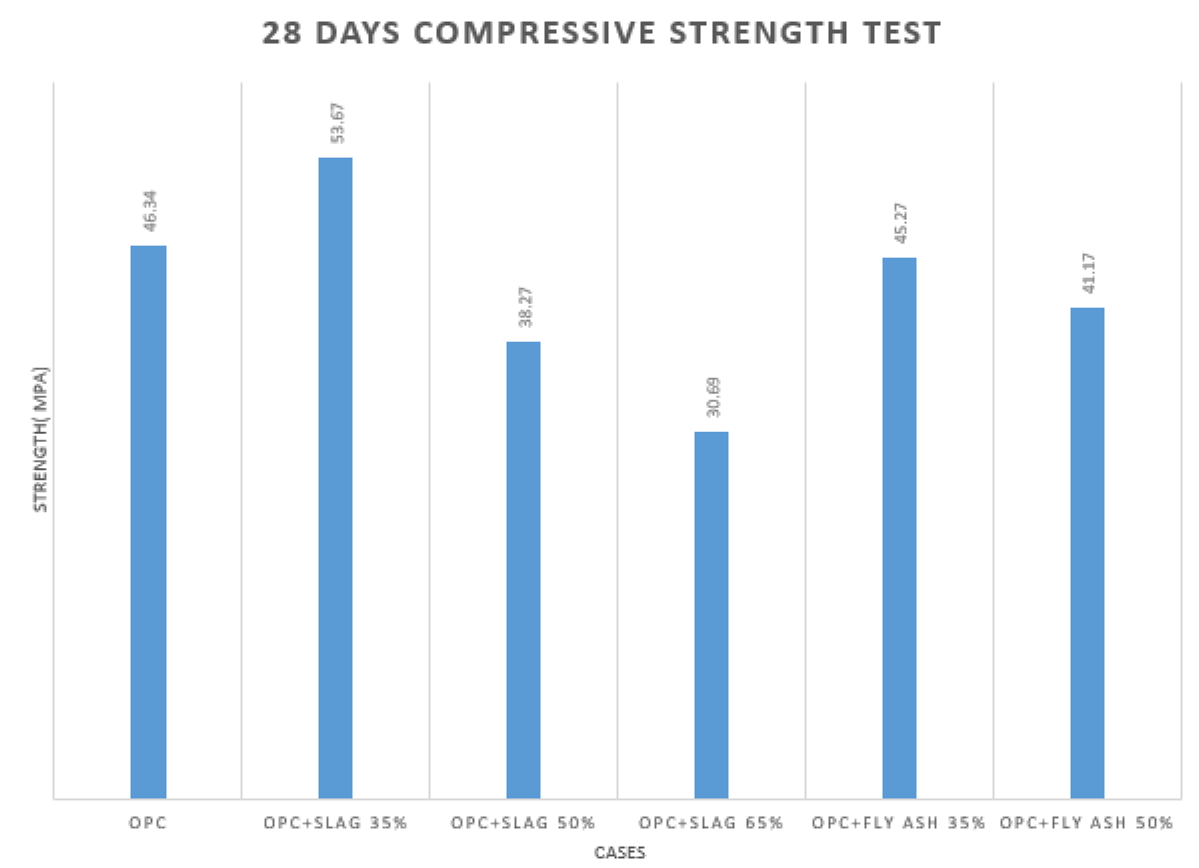

Fig: 28 days Compressive Strength

- **UPV**: SCM mixes demonstrated gradual densification over time, indicating good internal quality and reduced permeability.

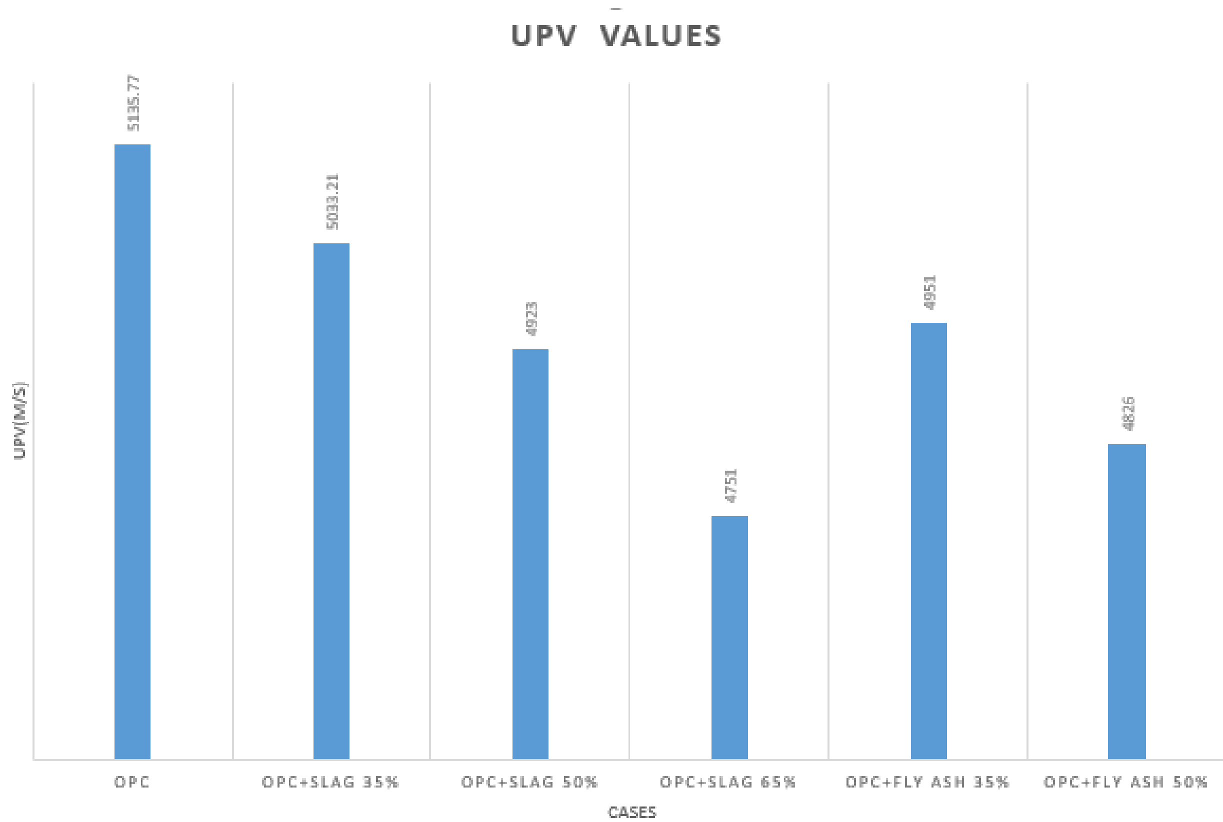

Fig: UPV values on 28 days

- **Chloride Resistance**: Slag mixes, especially OPC + Slag 65%, showed the lowest permeability and migration coefficients, indicating superior resistance to chloride ingress.

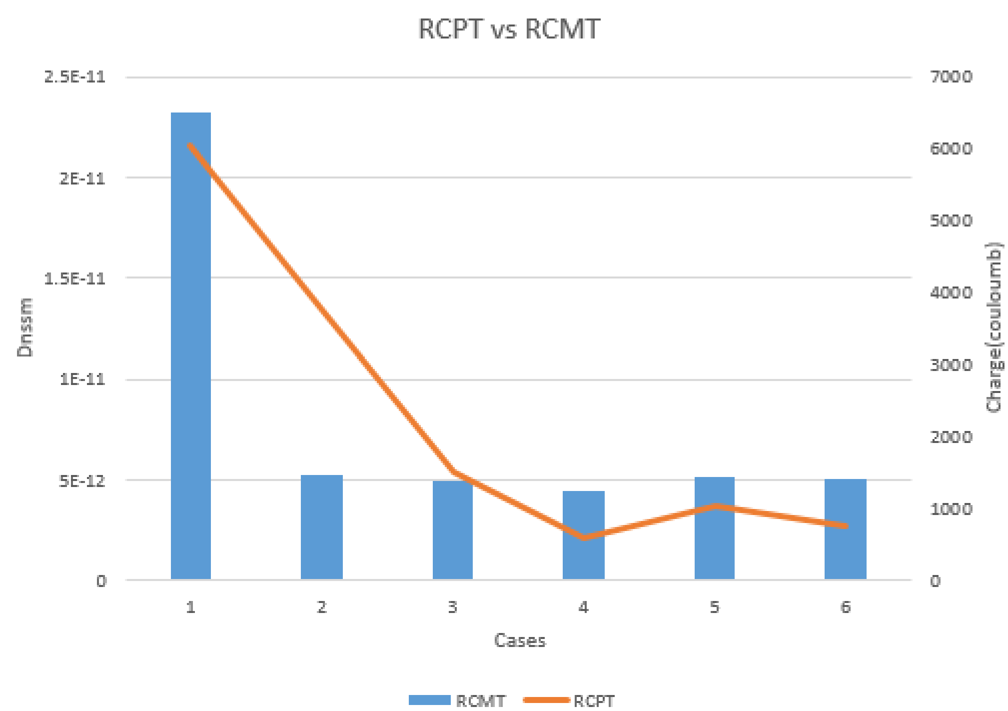

Fig: Showcase of penetration using both RCPT and RCMT

- **Chloride Profiling**: Chloride penetration depth was shallowest in slag mixes, further validating the improved resistance of SCM-containing concrete.

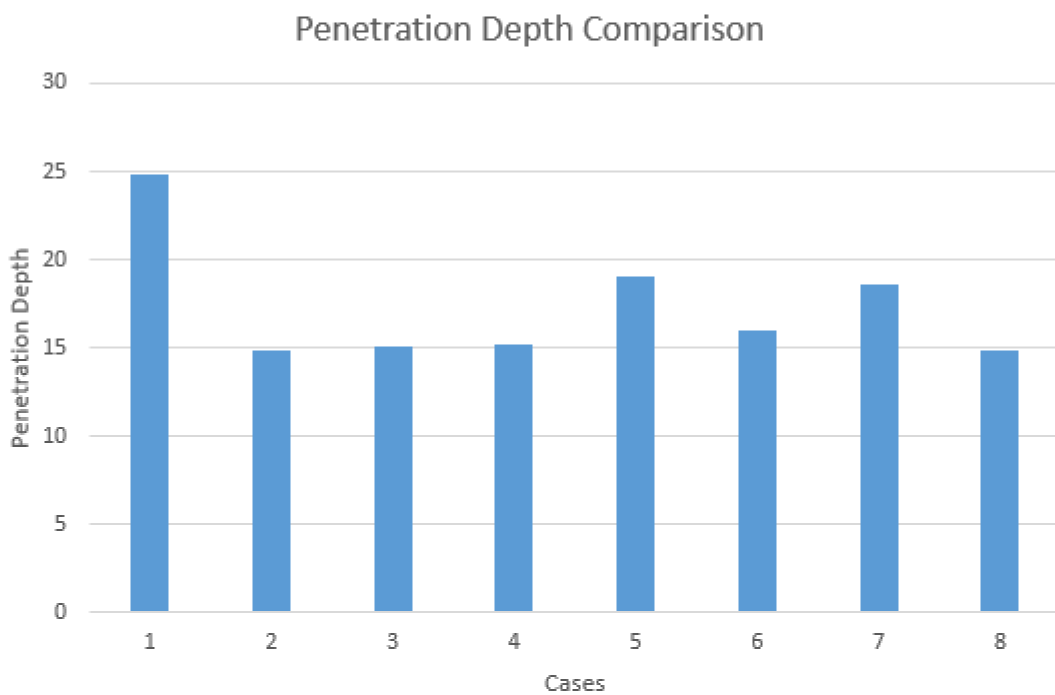

Fig: Penetration Depth Comparison

These findings suggest that incorporating SCMs, particularly at higher slag replacement levels, is effective in enhancing the durability of concrete in chloride-rich environments.

Chapter 5: Discussion

The purpose of this chapter is to analyze the results obtained from compressive strength, UPV, Rapid Chloride Penetration Test (RCPT), Chloride Migration Test, and chloride profiling in the context of improving concrete durability through the use of supplementary cementitious materials (SCMs). By understanding the effects of different SCM proportions on chloride resistance, this research aims to provide practical recommendations for concrete mix design, particularly for environments exposed to chloride.

5.1 Strength Development and its Implications for Durability

The compressive strength results across different mixes provide insight into the impact of SCMs on the mechanical properties of concrete. The findings indicate that mixes containing higher proportions of slag or fly ash exhibited slower early strength gain, likely due to the delayed hydration characteristics of SCMs. However, by 28 days, mixes such as **OPC + Slag 35%** and **OPC + Slag 65%** achieved strengths comparable to or even higher than the OPC mix.

The strength development patterns observed align with previous research, which suggests that while SCMs may reduce early-age strength, they contribute to higher long-term strength due to continued pozzolanic and hydraulic reactions. The enhanced strength at later ages indicates a denser, more refined microstructure, which has implications for chloride resistance, as denser concrete typically exhibits lower permeability and reduced susceptibility to chloride ingress.

The results suggest that mixes with **35% to 65% slag** content provide a balance between strength gain and durability. The higher long-term strength of SCM-containing mixes supports their use in structures exposed to aggressive environments, as it directly correlates with better durability and resistance to chloride penetration.

5.2 Influence of Supplementary Cementitious Materials on Chloride Resistance

The results from RCPT, chloride migration, and chloride profiling tests indicate that SCMs, particularly slag, significantly improve the chloride resistance of concrete. The following observations highlight the influence of SCMs on reducing chloride ingress:

- **Slag Effect**: The RCPT results showed a substantial reduction in chloride permeability for mixes containing slag. For instance, **OPC + Slag 65%** recorded the lowest charge passed in the RCPT test and exhibited the shallowest chloride penetration in the chloride profiling test. The addition of slag refines the pore structure, decreasing permeability and enhancing durability against chloride ions. The combination of pozzolanic and latent hydraulic properties in slag creates a denser, less porous matrix that limits chloride migration pathways.
- **Fly Ash Effect**: Fly ash also contributed to improved chloride resistance, albeit less effectively than slag in this study. **OPC + Fly Ash 35%** showed intermediate RCPT and chloride migration test results, performing better than pure OPC but not as well as the slag mixes. The use of fly ash refines the concrete microstructure, which reduces chloride ion transport, but the extent of improvement varies based on the type and fineness of the fly ash. While effective, fly ash does not produce the same degree of refinement as slag, resulting in moderate chloride resistance.

Overall, the findings confirm that both slag and fly ash can improve chloride resistance, with **higher slag content (65%)** offering the most effective enhancement. The differences observed between the two SCMs underscore the importance of selecting SCM types and replacement levels based on the specific durability requirements of a structure.

5.3 Life Cycle Implications of Enhanced Durability

One of the primary goals of this research is to understand how different cementitious compositions impact the life cycle of concrete structures, particularly those exposed to chloride environments. The improved chloride resistance observed in slag and fly ash mixes has significant life cycle implications.

1. **Reduced Maintenance and Repair Costs**: By reducing chloride ingress, concrete mixes containing SCMs lower the risk of steel reinforcement corrosion, which is a leading cause of structural deterioration in chloride-exposed environments. Enhanced chloride resistance translates to fewer maintenance interventions, reducing both the financial and environmental costs associated with repairs and replacements.
2. **Extended Service Life**: The use of SCMs, especially at higher slag contents, is shown to extend the service life of concrete structures. As chloride ingress is slowed, the durability of the structure is preserved for a longer period. This extension of service life is particularly valuable in infrastructure projects, where long-term durability is critical.
3. **Sustainability Benefits**: Using SCMs such as slag and fly ash also supports sustainability by reducing reliance on Portland cement, which is energy-intensive to produce and contributes to carbon emissions. By partially replacing OPC with SCMs, this study promotes the adoption of more environmentally friendly concrete mixes that enhance durability while reducing the overall environmental impact of concrete production.

These life cycle benefits reinforce the need to adopt SCM-containing mixes, particularly for structures in marine or de-icing environments. The findings support a shift towards more sustainable, durable concrete solutions that align with global efforts to reduce the carbon footprint of the construction industry.

5.4 Comparison of Performance Between Slag and Fly Ash Mixes

The comparative analysis of slag and fly ash mixes reveals distinct performance differences:

- **Slag Mixes**: Slag mixes consistently outperformed fly ash mixes in chloride resistance tests, particularly in the RCPT and chloride migration tests. The slag mixes showed a refined pore structure, which contributed to lower chloride diffusion rates and enhanced durability. This outcome suggests that slag, with its hydraulic properties, may be better suited for concrete structures with high durability demands.
- **Fly Ash Mixes**: Fly ash mixes also demonstrated improved chloride resistance over pure OPC but were less effective than slag mixes. The pozzolanic nature of fly ash contributes to long-term strength and moderate durability benefits. Fly ash may be more suitable for applications where moderate chloride resistance is acceptable, or where sustainability considerations (e.g., the use of a byproduct from coal combustion) take precedence.

The comparative analysis indicates that **slag should be prioritized over fly ash in cases where high chloride resistance is required**. However, for general construction where moderate durability is sufficient, fly ash provides a viable alternative.

5.5 Limitations of the Study

While the findings of this study provide valuable insights, there are several limitations that should be considered:

- **Laboratory Conditions vs. Real-World Environments**: The tests were conducted under controlled laboratory conditions, which may not fully replicate real-world environments. Factors such as temperature fluctuations, moisture variations, and cyclic loading in actual field conditions could impact the chloride ingress and durability of concrete.
- **Long-Term Performance**: This study focused on short-term durability indicators (up to 28 days), which limits insights into the long-term performance of the SCM mixes. Future studies should extend the curing and exposure periods to assess durability over years.

- **SCM Variability**: The properties of slag and fly ash can vary depending on their source, processing, and fineness. This study used specific types of slag and fly ash, and results could vary with different materials. Thus, the findings should be generalized cautiously, and further testing with different SCM sources is recommended.
- **Normal Strength Concrete**: All the data used and gathered during testing and data analysis were for normal strength concrete specimen. We did not use high strength and ultra-high performance concrete in our testing. So, the findings of this study is applicable to only normal strength concrete. The behavior of concrete and result of study may change for HPC and UHPC.

5.6 Practical Recommendations

Based on the findings of this study, the following practical recommendations can be made:

- **For High-Durability Structures**: Use concrete mixes with 35-65% slag replacement, as they demonstrate the best performance in terms of chloride resistance and strength development. This is ideal for structures exposed to aggressive chloride environments, such as marine structures and bridges in coastal areas.
- **For Moderate Durability Requirements**: Fly ash blends (particularly around 35% replacement) provide moderate improvements in chloride resistance and sustainability benefits. These mixes are suitable for general construction where extreme durability is not essential.
- **Further Research on SCM Mix Design**: To maximize the durability benefits of SCMs, further studies should investigate the optimal balance of slag and fly ash combinations, as well as the effects of additional additives that could enhance chloride resistance.

5.7 Summary

The discussion highlights the role of SCMs, particularly slag, in enhancing the durability and life cycle of concrete structures exposed to chloride environments. The findings demonstrate that higher slag content provides significant improvements in chloride resistance, strength, and overall sustainability. Fly ash also offers benefits, though to a lesser extent than slag. The life cycle and sustainability implications of these improvements make SCMs a valuable addition to concrete mix design, particularly for infrastructure requiring long-term durability.

Chapter 6: Conclusion and Recommendations

The aim of this study was to investigate the effects of various supplementary cementitious materials (SCMs), specifically slag and fly ash, on the chloride resistance and durability of concrete. Through a series of standardized tests, including compressive strength, Ultrasonic Pulse Velocity (UPV), Rapid Chloride Penetration Test (RCPT), Chloride Migration Test, and chloride profiling, this research has provided insights into how different cement compositions affect the durability and life cycle of concrete structures in chloride-exposed environments.

6.1 Conclusion

The findings of this study demonstrate that incorporating SCMs, particularly slag, significantly enhances the chloride resistance of concrete. The primary conclusions are as follows:

1. **Improved Chloride Resistance with Slag**: Concrete mixes with higher slag content (35-65%) exhibited lower permeability and chloride migration rates compared to ordinary Portland cement (OPC) alone. **OPC + Slag 65%** performed best across all chloride resistance tests, suggesting that slag is highly effective in refining the concrete matrix and reducing ion migration pathways.

2. **Strength Development**: While SCM mixes, especially those with higher SCM content, displayed slower early strength gain, they achieved adequate or superior strength by 28 days. This trend indicates that slag and fly ash contribute to a more gradual hydration process, ultimately leading to a dense and durable matrix suitable for long-term applications.

3. **Fly Ash as a Moderate Alternative**: Although fly ash also improved chloride resistance, its performance was intermediate between OPC and slag blends. **OPC + Fly Ash 35%** showed reasonable chloride resistance, making fly ash a viable option for structures requiring moderate durability. However, in high-exposure environments, slag-based mixes are preferable.

4. **Life Cycle Benefits**: The use of SCMs, particularly at higher slag replacement levels, supports the life cycle extension of concrete structures by reducing maintenance needs and enhancing long-term performance. This contributes to sustainability by lowering the frequency of repairs, minimizing material consumption, and reducing the carbon footprint associated with concrete production and maintenance.

Overall, the study confirms that SCMs, particularly slag, offer significant benefits in terms of durability, sustainability, and life cycle cost-effectiveness. The adoption of SCM-based concrete in chloride-exposed environments can lead to more resilient and sustainable infrastructure.

6.2 Practical Recommendations

Based on the findings, several practical recommendations can be made for the construction industry:

1. **Adopt High Slag Content Mixes for Chloride-Exposed Structures**: For structures exposed to aggressive chloride environments (e.g., marine structures, coastal bridges), concrete mixes with **35-65% slag** replacement are recommended. These mixes demonstrated the best performance in chloride resistance tests and are likely to reduce the need for frequent maintenance.
2. **Use Fly Ash for Moderate Durability Requirements**: For general construction projects that do not face high chloride exposure, fly ash can be used as a cost-effective and sustainable alternative. **OPC + Fly Ash 35%** provides moderate chloride resistance and supports sustainable construction practices by reducing the carbon footprint.
3. **Optimize SCM Mix Design Based on Environmental Conditions**: The results suggest that the choice and proportion of SCMs should be tailored to the environmental conditions the structure will face. High slag content is ideal for high-chloride environments, while fly ash may be suitable for less demanding conditions.

4. **Prioritize SCMs for Sustainable Construction**: Given the sustainability benefits of SCMs, construction projects should prioritize using SCM-based concrete where possible. By reducing reliance on pure OPC, SCM mixes contribute to lower carbon emissions and better life cycle performance.

6.3 Future Research Directions

While this study provides valuable insights into the durability benefits of SCMs, several areas of research are recommended to further explore and optimize SCM-based concrete:

1. **Long-Term Performance Studies**: Future studies should focus on evaluating the long-term performance of SCM-based concrete under real-world conditions. Extending the study duration to several years would provide a more comprehensive understanding of how SCMs contribute to durability over extended periods.
2. **Impact of Different Sources and Types of SCMs**: This study used specific types of slag and fly ash, but the properties of SCMs can vary based on their source and processing. Research into different types of slag, fly ash, and other SCMs (e.g., silica fume) would help determine optimal SCM selections for various applications.
3. **Combination of SCMs and Additional Admixtures**: Investigating the effects of combining SCMs (e.g., slag and fly ash) with chemical admixtures designed to enhance chloride resistance could yield further improvements in durability. The interactions between SCMs and chemical admixtures, such as superplasticizers or corrosion inhibitors, warrant exploration.
4. **Field Studies on Real Structures**: Laboratory results are valuable but may not fully capture the complexities of real-world environments. Field studies on structures built with high SCM content would provide more accurate data on durability, particularly in high-chloride exposure locations.

5. **Economic and Environmental Life Cycle Assessment**: Future research could include a full economic and environmental life cycle assessment (LCA) of SCM-based concrete mixes, comparing the cost savings and environmental benefits to traditional OPC concrete. This would provide further evidence to support sustainable construction practices.

6.4 Final Remarks

This research demonstrates the potential of SCMs, particularly slag, to improve the chloride resistance and overall durability of concrete. By reducing chloride ingress, SCM-based mixes contribute to longer service lives, lower maintenance costs, and enhanced sustainability in concrete construction. The findings support a shift toward more resilient, environmentally-friendly concrete designs, particularly for infrastructure in aggressive environments. Adopting SCM-based concrete aligns with broader sustainability goals and offers a promising pathway toward building more durable, cost-effective, and sustainable infrastructure for the future.

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