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Durability of Low Carbon Concrete Mixtures

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16. Abstract

This report presents a study of the chloride resistance (durability) of concrete mixtures that may be used to achieve low-carbon requirements. 18 distinct concrete mixtures were evaluated, with a comprehensive testing regime encompassing fresh state properties (slump, setting time, air content, and fresh density), compressive strength, and durability indicators (salt scaling resistance and chloride ion diffusion). The objective was to assess the viability of low-carbon concrete systems under performance-based criteria relevant to large-scale infrastructure applications. Overall, the mixtures demonstrated strong performance across several criteria. The 77% slag blend emerged as the most effective, meeting all selective performance benchmarks while offering the lowest carbon cost. Notable alternatives include 40F, 50F, 60S, 65S, 60S/OA, and 50S/PLC, which also showed robust performance.

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Concrete, innovative concrete materials, supplementary cementitious materials

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1 Executive Summary

This report details the outcomes of the durability study on low carbon concrete systems, particularly focusing on the chloride resistance of innovative systems. 18 distinct concrete mixtures were evaluated, with a comprehensive testing regime encompassing fresh state properties (slump, setting time, air content, and fresh density), compressive strength, and durability indicators (salt scaling resistance and chloride ion diffusion). The objective was to assess the viability of low-carbon concrete systems under performance-based criteria relevant to large-scale infrastructure applications. Overall, the mixtures demonstrated strong performance across several criteria. The 77% slag blend emerged as the most effective, meeting all selective performance benchmarks while offering the lowest carbon cost. Notable alternatives include 40F, 50F, 60S, 65S, 60S/OA, and 50S/PLC, which also showed robust performance.

The research supports the conclusion that a diverse range of technological solutions can be effectively employed to produce durable, low-carbon concrete. Nonetheless, additional laboratory studies are essential to validate the performance of new combinations, given the current lack of consensus on their synergistic effects.

2 Introduction and Background

The environmental footprint of the concrete industry is substantial, with approximately 50% of primary energy and natural resource consumption [1,2], 30% of landfill-bound waste [3], 15% of freshwater resources [4], and 33–35% of greenhouse gas emissions (GHG) originating from its activities [5,6]. Projections indicate that, in response to escalating infrastructure and urban development needs, global consumption of portland cement could rise to 6 billion tons per year by 2060 [7]. To achieve sustainability via carbon neutrality, a key strategy involves producing modified concrete that uses less cement or aggregates and includes innovative materials.

Low Embodied Carbon Concrete (LECC) is designed to minimize carbon emissions by incorporating supplementary cementitious materials (SCMs) like fly ash, ground-granulated blast furnace slag (GGBFS), limestone, and ground glass pozzolan (GGP), which partially replace conventional portland cement. The substitution ratios vary depending on the type of SCM used. LECC comprises a new generation of concrete mixtures that integrate traditional and innovative design strategies to reduce embodied carbon beyond what is achievable with current industry standards [8]. LECC mixtures can be produced using a broad range of tools such as using locally available materials, optimizing aggregate gradations, reducing the total amount of binder, using supplementary cementitious materials (SCMs), and through CO_2 mineralization and utilization [9–14] . While there is no official industry standard defining LECC, emerging policies from local governments and transportation agencies are beginning to set embodied carbon limits for concrete, effectively encouraging the use of LECC design methods.

In prior research, the team studied the carbon footprint and performance of a range of concrete mixtures from the New York City Metro (NYCM) region. Results showed that the inclusion of supplementary cementitious materials (SCMs) led to notable carbon reductions, with ternary blends—comprising portland cement and two SCMs—being the most effective. According to existing scientific literature, these systems can be used without notably reducing the strength or durability of the concrete and often result in long-term improvements in strength and durability performance [17–22].

The research team focused on developing 20 LECC mixtures that demonstrate lower embodied carbon than compared to a standard portland cement system, for further testing. The proposed mixtures were based on a thorough review of relevant literature and an analysis of available aggregates within the NYCM region. The task included compiling background data on LECC concrete, detailing the methodology used for mixture development, and reporting both the mixture designs and their estimated embodied carbon.

The proposed mixtures leverage a broad spectrum of SCM strategies, including varying replacement levels of fly ash, slag, carbonated fly ash, and ground glass pozzolan. Ternary systems combining slag with either fly ash or GGP were also examined. Several formulations feature in-situ carbonate seeding via CarbonCure Technologies, while others incorporate aggregate optimization to reduce global warming potential (GWP) beyond the use of SCMs alone. A single mixture included recycled concrete aggregate (RCA) as a conceptual demonstration. Based on findings from 20 LECC mixtures, increasing SCM content remains the most effective strategy for lowering GWP. Nevertheless, technologies such as aggregate optimization, portland limestone cement substitution, and carbonate seeding offer additional pathways to reducing carbon intensity in systems already approaching SCM capacity limits.

This report summarizes the findings from the LCC durability project, which involved an experimental evaluation of proposed low-carbon concrete mixtures. The study assessed a range of fresh and hardened properties, including compressive strength, salt scaling resistance, and chloride diffusion. In addition to performance testing, the report includes a cost-of-CO_2 analysis for each mixture, based on their global warming potential (GWP). Drawing on both experimental results and environmental data, the report provides recommendations for future pilot projects that could implement low-carbon concrete systems.

3 Testing Materials and Methodology

3.1 Materials

3.1.1 Cementitious Materials

This study utilized a diverse range of cementitious materials. Type I portland cement (ASTM C150) [15] and Type IL portland limestone cement (PLC) (ASTM C595) [16] were both supplied by Lehigh Cement Corporation from their Nazareth Plant in Nazareth, PA. The calcium sulfoaluminate (CSA) cement (ASTM C1600), marketed as Rapidset, was sourced from CTS Cement Manufacturing Corporation. Supplementary cementitious materials, including a high calcium fly ash (ASTM C618) [17] and slag cement (ASTM C989) [18], were provided by Clayton Concrete Company's Allentown, NJ facility. Ground glass pozzolan (GGP) (ASTM C1866) [19] was supplied by Urban Mining, produced at their facility in Beacon Falls, CT. A representative chemical oxide analysis of each cementitious material is presented in Table 1.

Table 1. Chemical oxide analyses of cementitious materials

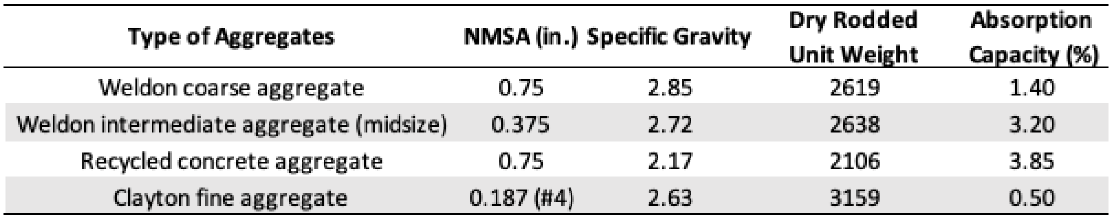
Chemical Amount or Property	Cementitious Material				
	Type I Portland Cement	Type IL Cement	Slag Cement	Fly Ash	Ground Glass Pozzolan
SiO_2	19.69%	17.67%	-	42.42%	71.70%
Al_2O_3	4.96%	4.36%	13.14%	20.94%	1.60%
Fe_2O_3	2.51%	2.11%	-	20.16%	0.50%
CaO	63.37%	61.74%	-	5.82%	11.10%
SO_3	3.57%	4.01%	1.40%	2.24%	0.10%
Na_2O	0.29%	0.37%	0.80%	1.10%	13.00%
K_2O	1.02%	0.92%	-	1.60%	0.50%
Sulfide S	-	-	0.72%	-	
MgO	2.90%	2.90%	-	0.71%	1.40%
Total Limestone	-	9.16%			
Loss on Ignition	0.92%	5.29%	-	2.83%	< 0.50%
28-Day Slag Activity Index	-	-	115 min.	-	
28-Day Strength Activity Index	-	-	-	83.90%	102%

3.1.2 Aggregates

This study used four aggregate systems. The coarse (¾ in. NMSA) and intermediate (⅜ in. NMSA) aggregates were supplied by Weldon Materials from their Watchung, NJ quarry. Fine aggregate came from Clayton Concrete Company's Allentown, NJ location. A recycled concrete aggregate (RCA) was provided by the NYC Department of Transportation, produced from waste concrete of an unknown origin. Aggregate properties are listed in

Table *2*.

Table 2. Aggregate properties of low carbon concrete systems



Type of Aggregates	NMSA (in.)	Specific Gravity	Dry Rodded Unit Weight	Absorption Capacity (%)
Weldon coarse aggregate	0.75	2.85	2619	1.40
Weldon intermediate aggregate (midsize)	0.375	2.72	2638	3.20
Recycled concrete aggregate	0.75	2.17	2106	3.85
Clayton fine aggregate	0.187 (#4)	2.63	3159	0.50

3.1.3 Admixtures

Admixtures were used to modify the properties of the concrete mixtures as needed. Sika ViscoCrete-6100, a high-range water-reducing admixture, was applied in dosages ranging from 10.3 to 75.7 oz. per 100 lbs of cementitious materials. SikaAir-260 served as the air-entraining admixture, with dosages between 1.1 and 4.3 oz. per 100 lbs. As presented in Table 4, all concrete mixtures employed various dosage levels of both air-entraining admixture and high-range water-reducing admixture.

Given the rapid setting behavior of CSA cement, citric acid (manufactured by Milliard) was used as a chemical retarder to improve its workability. Known for its effectiveness, citric acid extends the working time of concrete by roughly 15 minutes per 0.1% increase in dosage. To accommodate different CSA volumes, citric acid levels were tailored accordingly, with dosages ranging from 0.4% to 0.8% to achieve suitable slump and extended handling time.

3.2 Concrete Mixtures

In Table 3, the low carbon concrete mixtures are listed along with their mixture IDs (Mixture ID), shortened IDs (Short ID) for easier reference, and a brief description, while Table 4 summarizes the mixture design. Multiple batches of each mixture were cast, with slump, air content, and density measured for each one. Compressive strength tests were performed on all batches to ensure consistency between them.

Table 3. Description of low carbon concrete mixtures

Mixture ID	Short ID	Description
PC	PC	Baseline 100% portland cement binder mixture
FA_30%	30F	Baseline 30% fly ash binder mixture
SLAG_50%	50S	Baseline 50% slag binder mixture
FA_30%_OA	30F/OA	30% fly ash binder mixture utilizing particle packing theories to increase the volume of aggreagates
SLAG_50%_OA	50S/OA	50% slag binder mixture utilizing particle packing theories to increase the volume of aggregates
SLAG_50%_RCA	50S/RCA	50% slag binder mixture utilizing recycled concrete as coarse aggregates
SLAG_50%_PLC	50S/PLC	Binder mixture made up of 50% slag and 50% portland limestone cement
FA_40%	40F	40% fly ash binder mixture
FA_50%	50F	50% fly ash binder mixture
FA_40%_OA	40F/OA	50% fly ash binder mixture utilizing particle packing theories to increase the volume of aggregates
SLAG_60%	60S	60% slag binder mixture
SLAG_60%_OA	60S/OA	60% slag binder mixture utilizing particle packing theories to increase the volume of aggregates
SLAG_77%	77S	77% slag binder mixture
SLAG_65%	65S	65% slag binder mixture
GGP_30%	30GGP	30% ground glass pozzolan binder mixture
Ternary_FA_SLAG	38S/38F-Tern	Ternary binder system using 38% slag, 38% fly ash, and 25% portland cement
Ternary_SLAG_GGP	50S/15GGP-Tern	Ternary binder system using 50% slag, 15% ground glass pozzolan, and 35% portland cement
CSA	CSA	Rapid setting mixture using 100% calcium sulfoaluminate cement binder

Table 4. Mixture design of low carbon concrete systems

	Cementitious Materials (lb/yd^3)						Aggregates (lb/yd^3)				Admixtures (oz./100 lb cement)		
Mixture ID	Type I Portland Cement Content	Portland-Limestone Cement (Type IL cement)	Type F Fly Ash	Ground Granuluated Blast Furnace Slag	Ground Glass Pozzolan (Pozzotive)	Calcium Sulfoaluminate Cement	Weldon Coarse Aggregate	Midsize Aggregate	Clayton Fine Aggregate	Coarse Recycled Concrete Aggregate	Superplasticizer (High Range Water Reducer-Sika ViscoCrete-6100)	Air Entrainer (Sika Air-260)	Set Retarder (Milliard Citric Acid)
Baseline Mixtures													
PC	575						1836		1386		10.6-11.7	0.3-0.4	
FA_30%	400		175				1808		1365		10.4-12.8	0.7-1.0	
SLAG_50%	325			325			1738		1312		11.3-13.8	0.9	
Modified Baseline Fly Ash Mixtures													
FA_30%_OA	326		140				1466	700	1353		18.7-22.6	0.4-0.5	
Modified Baseline Slag Mixtures													
SLAG_50%_OA	238			238			1466	700	1353		24.2-26.9	0.2-0.3	
SLAG_50%_RCA	324			324					1314	1325	16.8-18.8	0.8	
SLAG_50%_PLC		325		325			1736		1311		19.2-19.5	0.8-0.9	
High Replacement Fly Ash Mixtures													
FA_40%	360		240				1930		1188		12.4-15.6	0.8-1.1	
FA_50%	300		300				1920		1181		21.3	0.9	
FA_40%_OA	279		186				1466	700	1353		26.4-29.8	0.6	
High Replacement Slag Mixtures													
SLAG_60%	240			360			1956		1203		18.7-21.3	0.9	
SLAG_60%_OA	218			327			1466	700	1353		43.7-47.7	0.8-1.0	
SLAG_77%	142.5			437			1978		1217		42.7-59.5	0.4	
SLAG_65%	203			377			1980		1218		18.1-25.2	0.6	
Ground Glass Pozzolan Mixture													
GGP_30%	350				150		2040		1308		27.4-28.3	1.1-2.0	
Ternary Mixtures													
Ternary_FA_SLAG	150		236	236			1967		1211		71.5-75.7	3.2-4.3	
Ternary_SLAG_GGP	225			288	81		1959		1309		46.2-52.6	2.3-2.8	
CSA Mixture													
CSA						700	1291		1279		10.3-11.4	0.4	0.8% by cement

3.3 Testing Methodology

3.3.1 Batching and Mixing Procedures

In the laboratory, concrete was prepared using a modified procedure based on ASTM C192 [20], employing a 0.11m^3 rotating drum mixer. Adjustments to the standard protocol included the initial introduction of air-entraining admixtures along with coarse aggregates into the mixer, followed by a 2-minute mixing period before proceeding with the standard mixing instructions. This modification was implemented to achieve more uniform air content levels. Multiple concrete batches were mixed to ensure enough specimens for testing purposes. Once mixed, the fresh properties of the concrete were evaluated, and then the mixture was poured into molds designated for testing hardened properties.

Before mixing, aggregates were saturated surface dry (SSD) for a minimum of 24 hours before use. The quantity of surface water was considered as part of the required mixing water. The surface moisture of aggregates was determined using ASTM C566 [21], taking into account the appropriate absorption of fine aggregate and coarse aggregate based on ASTM C128 and ASTM C127 [22,23]. Each aggregate size was processed separately to ensure the attainment of a suitable gradation.

The mixing process began with the addition of coarse aggregates, a portion of the mixing water, and the required admixture solution before initiating mixer rotation. After a few revolutions, the remaining fine aggregate and half of the water were added with the mixer stopped. The complete mixture was then blended for 3 minutes, allowed to rest for 3 minutes, and mixed again for an additional 2 minutes. A critical consideration during the mixing procedure was the need to cover the mixer opening during the rest period to prevent moisture loss through evaporation, which could alter the effective water content. For calcium sulfoaluminate (CSA) systems, a modified protocol was employed due to their rapid initial set. As a result, all CSA mixing operations were completed within 3 minutes.

Furthermore, admixtures were introduced to promote uniform appearance and help reach the target consistency of each concrete mixture. In cases where water had to be added incrementally—resulting in prolonged mixing—the batch was deemed unsuitable and discarded. A new batch was promptly prepared to proceed with consistency evaluations under standard conditions.

3.3.2 Casting of Specimens

Various types of specimen molds were used in this study, including disposable cylinders and prisms. All concrete specimens were prepared according to ASTM C192 [20]. In this study, disposable concrete cylinder molds measuring 4 in. x 8 in. were used for the determination of compressive strength, and chloride ion diffusion. For salt scaling testing, wooden prism molds measuring 3 in. x 11 in. x 11 in. were used. For containers of mortar for setting time testing, the lateral and height dimensions should be larger than 6 in. [24].

3.3.3 Fresh Properties Testing

For each concrete mixture, the slump, air content, fresh density, setting time, temperature, and water-to-binder (w/b) ratio were assessed in accordance with the relevant standardized procedures—namely ASTM C143, ASTM C231, ASTM C138, ASTM C403, ASTM C1064, and AASHTO T318—thereby ensuring that the evaluations adhered to established guidelines and maintained methodological consistency throughout the testing process [21–26].

3.3.3.1 Testing of slump

To prepare for slump testing, the mold was placed on a smooth, level, and moist surface that did not absorb water. Concrete was added in three even layers, each making up about a third of the total volume and spread carefully to avoid segregation. After placing each layer, the concrete was rodded 25 times evenly across the mold. The mold was then removed by lifting it straight up 12 in. in 2 seconds, with no tilting or twisting. The entire slump test was completed within 2.5 minutes. Slump was measured as the vertical distance between the top of the mold and the displaced center of the specimen's top surface. If the specimen exhibited excessive subsidence or shearing, the test was considered invalid and repeated using a different portion of the sample.

3.3.3.2 Testing of air content

Air content was measured in accordance with ASTM C231 [25]. The measuring bowl was pre-dampened and filled with concrete in two equal layers. Each layer was rodded 25 times uniformly, followed by tapping the sides of the bowl to eliminate voids and release trapped air. Excess concrete was struck off, and water was added to fill the top section of the air meter. The final reading was then recorded accordingly.

3.3.3.3 Testing of setting time

The setting time of concrete mixtures was determined in accordance with ASTM C403 [24]. Surface bleed water was first removed from the mortar using a pipet. Penetration resistance tests were conducted using a standardized apparatus, inserting a needle to a depth of 1 in. (25 mm) into the mortar. The applied force and corresponding time were recorded to calculate penetration resistance. Testing began approximately 3 to 4 hours after mixing and continued until the resistance exceeded 4000 psi. The results were plotted, and regression analysis was used to verify conformity with expected setting time trends.

3.3.4 Mechanical Properties Testing

Compressive strength measurements were carried out by the MatSLab research team at NJIT in accordance with ASTM C39/C39M [26]. The specimens were prepared in 4 in. × 8 in. plastic cylinder molds to measure the compressive strength at designated curing periods. The results obtained are utilized for quality control in concrete proportioning, mixing, and placement operations, ensuring compliance with specifications, evaluating the effectiveness of admixtures, and similar purposes. To ensure data accuracy, ASTM standards impose strict controls on specimen dimensions, loading rates, and acceptable result variations. Prior to testing, specimens were conditioned to maintain a consistent moisture level, and the diameter error was kept within a 2% tolerance. The load was applied continuously and smoothly, without any shock, until the load indicator registered a steady decrease, and the specimen exhibited a clearly defined fracture pattern.

3.3.5 Durability Properties Testing

3.3.5.1 Testing of chloride ion diffusion

We evaluated the chloride contents at certain depths along with diffusion coefficients of each chloride ponded concrete specimens in accordance with ASTM C1556 and ASTM C1152 [27,28]. The main aim is to determine the apparent chloride diffusion coefficient and surface chloride-ion concentration. This involves acquiring a sample of cementitious mixture, segregating it into test and initial chloride-ion content specimens, and then exposing, grinding, and analyzing the layers of the sealed test specimen. The test utilized cylindrical specimens with dimensions of 4 in. × 8 in., allowing each specimen to be tailored to the specific requirements of its respective evaluation method. All specimens were cured for 180 days in a lime-saturated solution at 23 ± 2°C and 100% relative humidity. After curing, the specimens were cut to a thickness of 3 in. (75 mm) from the middle section of the cylinders. Before sealing, the specimens were kept in the 50 ±3 % relative humidity chamber for about 24 hours. To ensure unidirectional chloride ingress, the sides and bottom surfaces were sealed with an epoxy coating, allowing chloride ions to penetrate only through the top face. Once the epoxy coating reached to touch-dry condition or properly cured, samples were then immersed in the sodium chloride exposure solution with a mass fraction of 14.2%. The reported exposure time is a minimum of 35 days; however, due to the incorporation of SCMs in the concrete, the exposure time should be appropriately extended. Therefore, the exposure time was set at 56 days for the study.

Following the 56-day exposure time, the test samples were retrieved and dried at 23 ± 2°C with a relative humidity of 50 ±3 % for at least 24 hours. Once properly dried, thin layers were ground parallel to the exposed surface using a milling machine. Due to a water-cement ratio of 0.4, as per ASTM C1556 specifications [27], grinding was required to a depth of 0.79 in. (20 mm), resulting in eight layers of concrete powder. However, this test considered grinding off to an additional layer, making a total of nine layers with a depth of 0.89 in. (22.5 mm) from the top surface. In the chemical test, titration was done using a 0.05N silver nitrate solution to determine the chloride ion concentration. The goal of the test is to quantify the apparent chloride diffusion coefficient and the surface chloride-ion concentration. To achieve this, a cementitious sample is collected, and divided into control and test specimens, and the sealed test specimen is then exposed, sectioned layer by layer, and analyzed for chloride content.

The testing procedure involved dissolving approximately 10 g of pulverized sample (passing an 850-µm or No. 20 sieve) in a 250 mL beaker with 75 mL of water and 25 mL of (1+1) nitric acid followed by stirring to break up lumps. Three drops of methyl orange indicator were introduced, and nitric acid was adjusted dropwise until a persistent pink color is achieved, followed by some additional drops. The covered mixture was briefly boiled for a moment to solubilize chlorides and then cooled. The solution was then filtered through a coarse-textured filter paper, rinsed twice with water, and cooled to room temperature. Electrodes were pre-calibrated in water to establish an approximate equivalence point (~20 mV below mid-scale). To the cooled filtrate, 2.00 mL of 0.05 N sodium chloride standard solution was added, and the mixture was titrated incrementally with standardized 0.05 N $AgNO_3$ using a buret while stirring magnetically. Millivolt readings are recorded after each 0.20 mL $AgNO_3$ addition near the equivalence point, continuing until three readings beyond the equivalence point confirm the titration curve. The precise equivalence point is calculated from the recorded data, ensuring temperature consistency to minimize solubility variations.

3.3.5.2 Testing of salt scaling resistance

In addition, ASTM C672 [29] prescribes testing methods relating to determination of scaling resistance of concrete surfaces exposed to deicing chemicals. This method allows the assessment of the impact of mixture proportioning, surface treatment, curing, or other factors on scaling resistance. The test was performed on specimen of concrete blocks measuring 3 in. × 11 in. × 11 in. In this study, the exposure solution consisted of 40g anhydrous calcium chloride in 1L of water, covering the flat surface by 0.25 inches. Each cycle lasted for 24 hours, with 18 hours of freezing followed by 6 hours of thawing at 23°C and 55% humidity in a curing chamber. After every five cycles, a visual examination was done, and the solution was replaced. The complete 50 cycles were sufficient to evaluate a surface treatment. To maintain the salty solution on the surface, plastic rectangles for storage were attached around the prisms using silicate glue.

4 Results and Discussion

4.1 Fresh Properties of Proposed Systems

4.1.1 Workability

To evaluate the workability of the systems, slump was measured directly after mixing for every batch of all concrete mixtures. **Error! Reference source not found.** presents the slump for each batch. The slump values varied from 0.5 inches to 9 inches across all batches and mixtures. The average slump across all batches for each mixture revealed that the 65S system had the lowest average at 1.56 in., and the ternary-fly ash-slag mixture had the highest average at 8.19 in. A variety of parameters can affect slump, such as air content, aggregate moisture state and surface charge, fines concentration, environmental conditions within the laboratory (e.g., relative humidity and temperature), and the performance characteristics of any admixtures used. It is also important to note that the slump of laboratory-mixed concrete does not serve as an accurate predictor of the slump in ready-mix truck mixed concrete. As such, slump is not a strong indicator of hardened concrete performance. Laboratory slump testing is most valuable for determining whether a mixture can achieve the necessary workability in the field. The results show that good workability was achieved without segregation across all mixture designs. Mixtures with higher SCM replacement levels needed greater amounts of water-reducing admixtures for optimal workability.

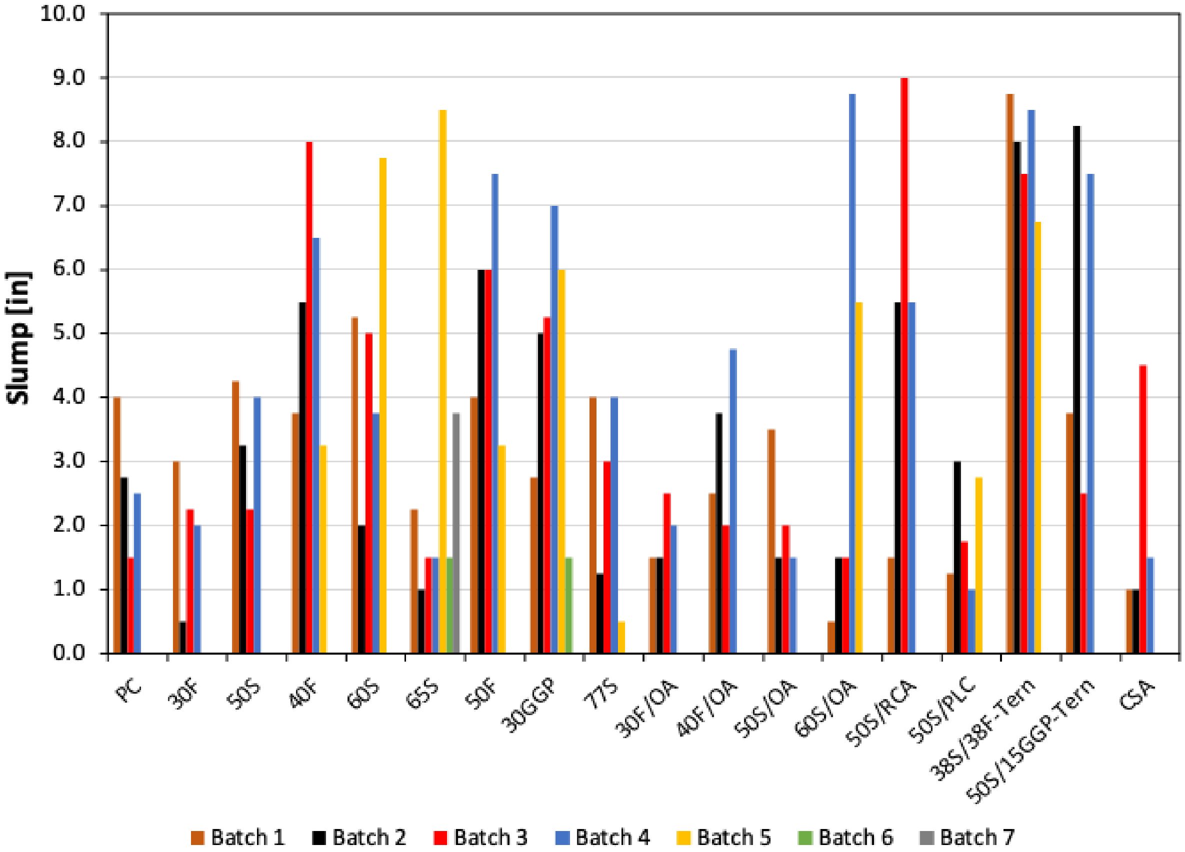


Figure 1. Slump of concrete mixtures

4.1.2 Setting Time

Initial and final setting times are reported in Figure 2 for all mixtures except the CSA system. Due to the inherently rapid setting characteristics of CSA cement, citric acid was used as a set retarder during laboratory testing to provide the NJIT team with sufficient working time for specimen casting. As a result, the recorded setting times for the CSA system were not considered representative of field performance and have been excluded from comparative analysis. Among all systems tested, the 60S system demonstrated the most rapid setting behavior, reaching initial set in 260 minutes (4.33 hours) and final set in 335 minutes (5.58 hours). Conversely, the 38S/38F-Tern system required the most time to set, with an initial set recorded at 555 minutes (9.25 hours) and a final set extending to 755 minutes (12.58 hours). The minimum initial setting time observed across all mixtures—260 minutes— is sufficient to accommodate essential pre-set operations, including placing, finishing, and the initiation of curing. Prolonged initial setting times in the 30GGP, 40F/OA, 38S/38F-Tern, and 50S/15GGP-Tern mixtures may lead to poor finishing and curing due to moisture loss during extended waiting periods. These delays can also increase labor costs, making these systems impractical for time-sensitive applications unless set-accelerating admixtures are used.

Excessively long final setting times can lead to construction delays or hinder key operations such as saw cutting and site access, depending on the type of project, seasonal conditions, and site logistics. In this study, four mixtures—30GGP, 40F/OA, 38S/38F-Tern, and 50S/15GGP-Tern—exhibited final setting times exceeding 10 hours. Given these extended durations, contractors may wish to consider strategies for accelerating set times in these mixtures or avoid their use in applications where construction timing is critical.

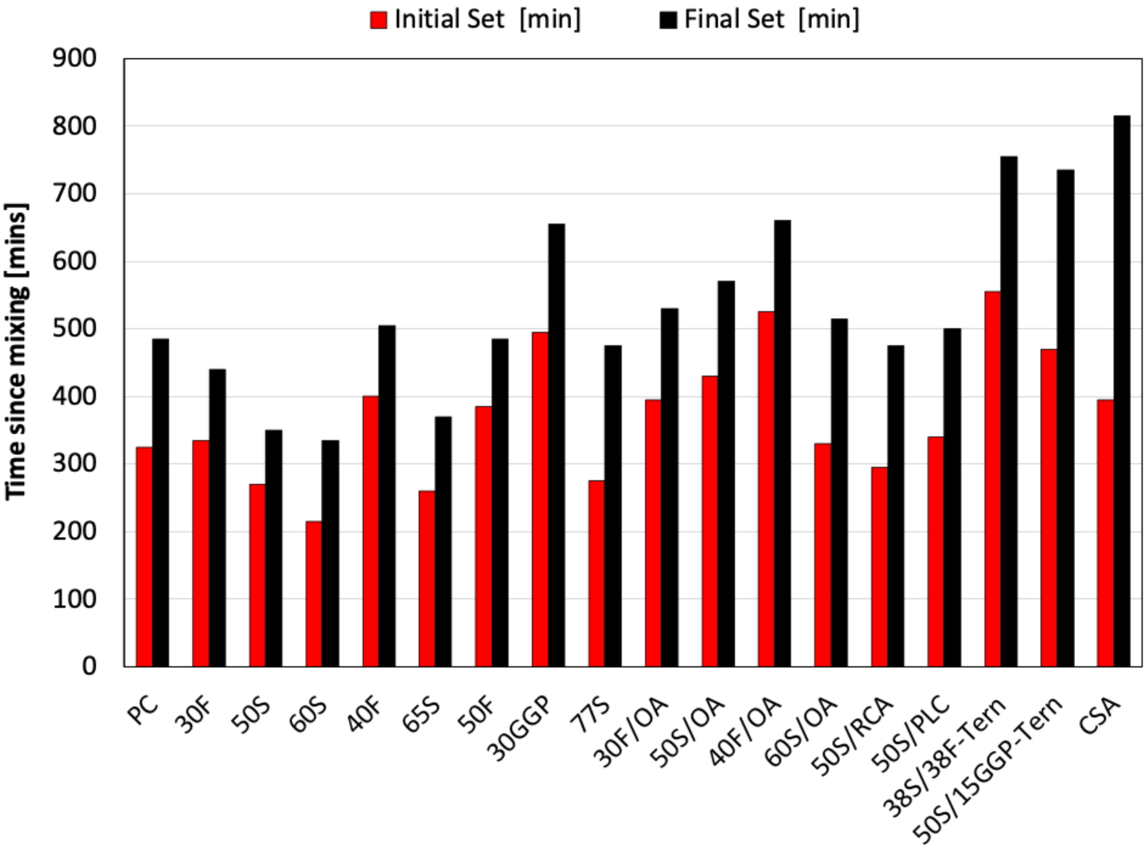


Figure 2. Setting time of concrete mixtures

4.1.3 *Air Content*

The air content of ready-mixed concrete was evaluated immediately after mixing for all batches across each mixture, ensuring consistency in the evaluation of fresh-state properties conforming to ASTM C231 [25]. As shown in Figure 3, the air content for each batch of concrete from all tested systems is depicted, offering insight into the variation in air entrainment across the mixtures.

Across all batches and mixtures, air content values ranged from 4.5% of the total concrete volume—recorded in Batch 1 of the Ternary-Slag-GGP system—to 9.5% in Batch 3 of the 40F system. Notably, concrete produced using the 60S system exhibited the highest average air content at 7.5%, whereas the PC system demonstrated the lowest average across all batches, at just 5.4%. Achieving adequate air entrainment was challenging in systems containing slag and GGP, requiring extra admixture doses, though the overall median air content across all mixtures was 6.3%. Because ready-mix trucks commonly experience a reduction in air content during the delivery window as a result of continued mixing it is recommended that higher doses of air-entraining admixtures than those used in this study be considered during trial batching for field applications to ensure compliance with required air entrainment levels.

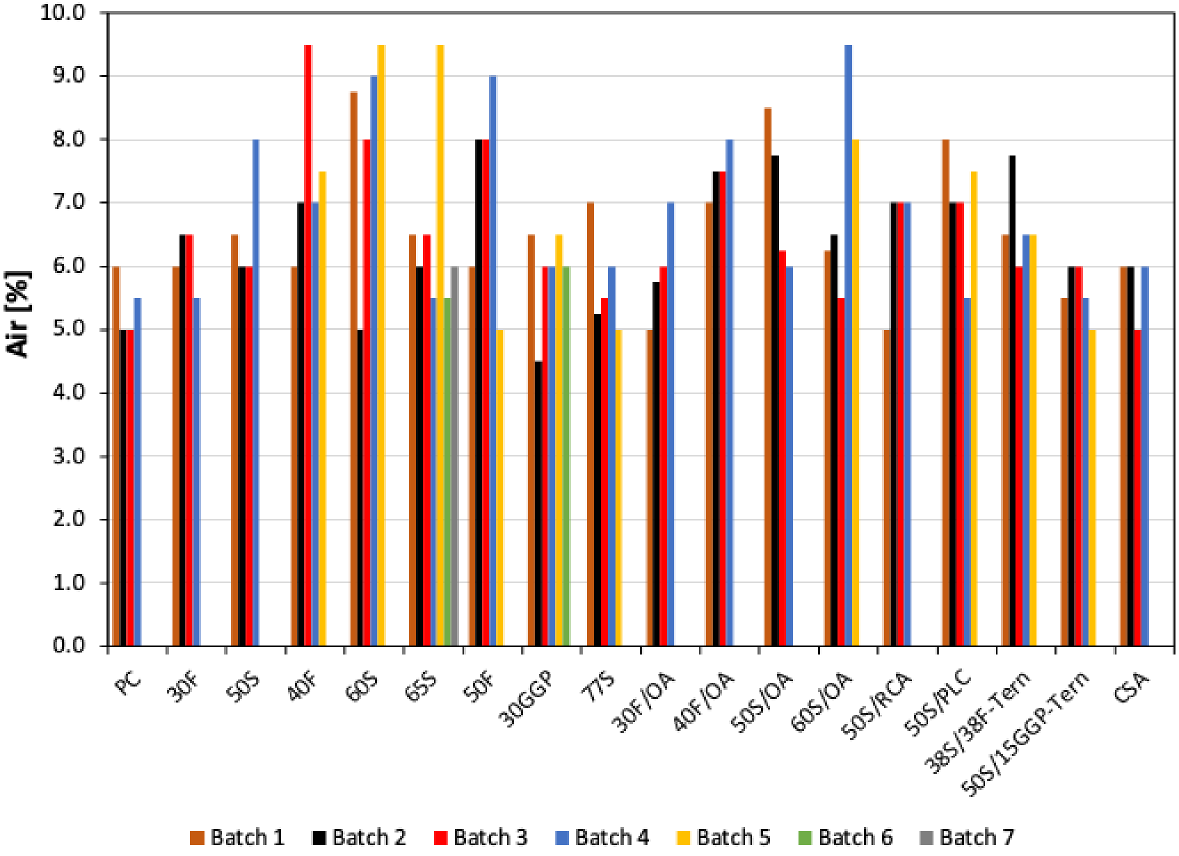


Figure 3. Air contents of concrete mixtures

4.1.4 Fresh Density

The fresh densities of freshly produced concrete were measured according to ASTM C138 [30] to serve as a quick and reliable quality control check to verify that the mix has been batched correctly. The measured fresh densities ranged from 0.083 lb/in^3 (50S/RCA) to 0.089 lb/in^3 (30GGP), indicating a consistency in material composition and mixing across different systems. Deviations in the measured densities may signal potential issues such as excess air content, or segregation, all of which can impact the performance and durability of the hardened concrete.

4.2 Hardened Properties of Proposed Systems

4.2.1 Compressive Strength

Figure 4 summarizes the average compressive strength performance of each mixture across multiple curing intervals: 7, 14, 28, 56, 90, and 180 days. A commonly used benchmark for general construction is achieving a 28-day compressive strength of at least 4,000 psi.

Except for the 40F/OA system—which required 56 days to exceed 4000 psi—all mixtures achieved this compressive strength by the 28-day mark. Although long-term strength performance was generally strong, construction practices often demand early strength gain to proceed with critical operations like formwork removal. At 7 days, several systems fell short of 4000 psi: 40F (3810 psi), 30F/OA (3880 psi), 40F/OA (2904 psi), and 50S/OA (3469 psi). Most systems demonstrated the potential to meet early strength targets needed for timely construction. However, only the baseline PC system achieved early-age compressive strengths above 5000 psi, indicating that such performance may not be feasible in SCM-based systems unless high-performance concrete technologies are employed.

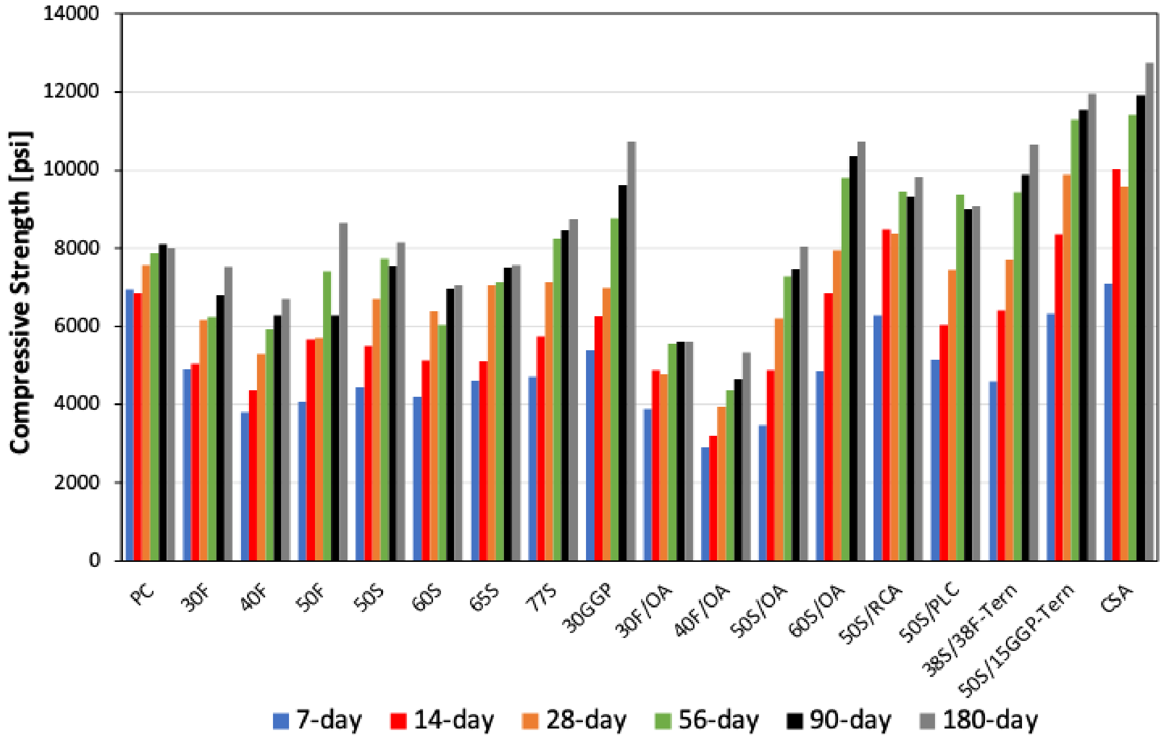


Figure 4. Average compressive strengths of concrete mixtures

Among the tested systems, 60S/OA and 50S/RCA achieved the highest compressive strengths at 28 days, both exceeding 8300 psi. Long-term performance peaked with the 30GGP system, which reached 9625 psi at 90 days. These high strength results indicate that there may be opportunities to reduce cement or total binder content without compromising structural performance. Overall, systems incorporating high SCM replacement levels consistently reached higher long-term compressive strengths than baseline mixtures such as 50F, 30F, 77S, and 50S. These results challenge the common assumption that high-strength concrete requires high portland cement contents and suggest that engineers could support a broad range of applications—including those requiring high strength—while reducing embodied carbon.

4.2.2 Chloride Diffusion

Error! Reference source not found., Figure 6, Figure 7, Figure 8, Figure 9, Figure 10, and Figure 11 summarize the findings of chloride diffusion test to measure the amount of chloride ingress in representative concrete specimens. Each test result containing low carbon concrete systems was compared to the 100% Portland cement baseline mixture or PC system. The term "chloride diffusion" describes the gradual flow and buildup of chloride ions into the concrete matrix, usually by means of seawater or deicing solutions. When these chloride ions get to the steel reinforcement that is incorporated in the concrete, they may break down the passive oxide layer that typically shields it and cause corrosion [31]. Chloride transport in concrete occurs through capillary absorption, hydrostatic pressure, and diffusion. Capillary action draws in chlorides during wetting, hydrostatic pressure forces them inward under external loads, and diffusion moves ions from high to low concentration in saturated pores [32]. Chloride ingress in concrete is primarily influenced by factors such as permeability, water-to-binder ratio, use of SCMs, and exposure conditions like chloride concentration and wetting-drying cycles. Additionally, concrete cover depth, curing quality, and the presence of cracks in the hardened concrete matrix play critical roles.

As it can be observed from the **Error! Reference source not found.** to Figure 11, at a depth of 0.40 in. or less, most samples exhibited chloride concentrations below 0.1% by mass of concrete after 56 days of exposure to the chloride solution. While most systems demonstrated comparable chloride behavior, the 50S/OA and PC systems deviated from this trend. Notably, the 50S/OA mix had a high initial surface chloride content of 0.99%, which rapidly decreased after 0.19 in. of penetration. The lowest initial chloride content was recorded at 0.31% for the 50S/PLC system, and ternary systems, such as 38S/38F-Tern and 50S/15GGP-Tern, exhibited less chloride contents compared to other systems. Additionally, chloride content in the PC specimen remained above 0.1% until 0.59 in. of depth, with a slower reduction rate than other mixes—highlighting its higher permeability. According to the literature [30], corrosion is likely to initiate when chloride content at the reinforcement level surpasses 0.125% by concrete mass. These findings support the conclusion that SCM inclusion markedly improves concrete durability. As the depth approached to 0.15-0.2 in. or more, all systems started to show a gradual decline in the chloride contents, indicating the reduced permeability effect upon the inclusion of SCMs in concrete.

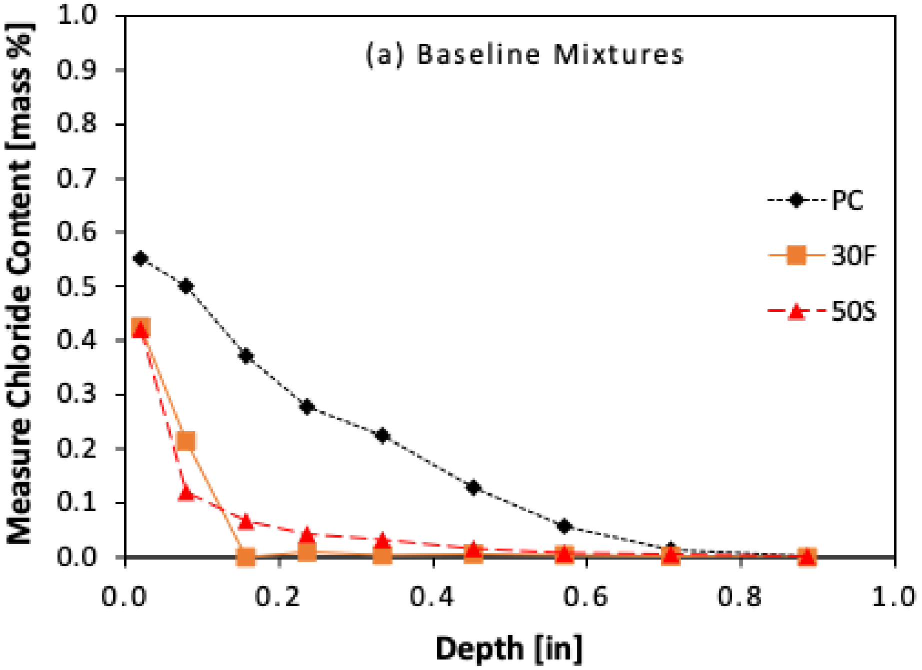


Figure 5. Measured chloride contents at designated depths (baseline mixtures)

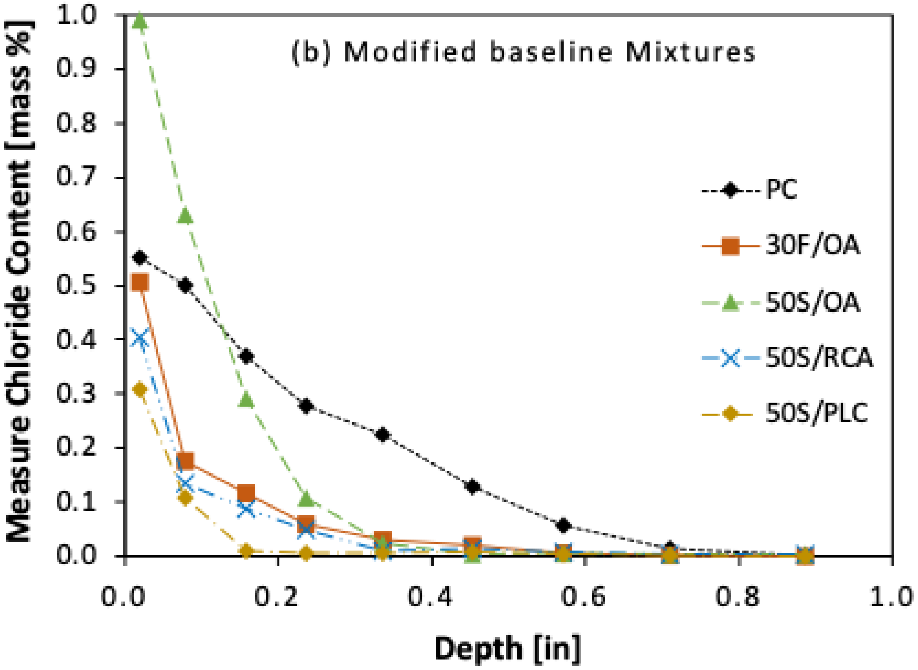


Figure 6. Measured chloride contents at designated depths (modified baseline mixtures)

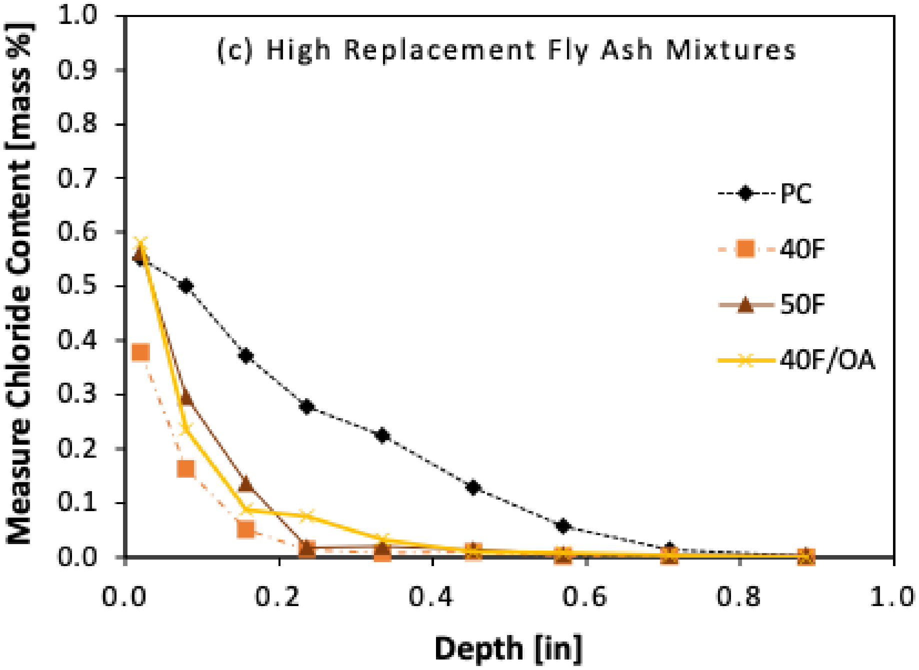


Figure 7. Measured chloride contents at designated depths (high replacement fly ash mixtures)

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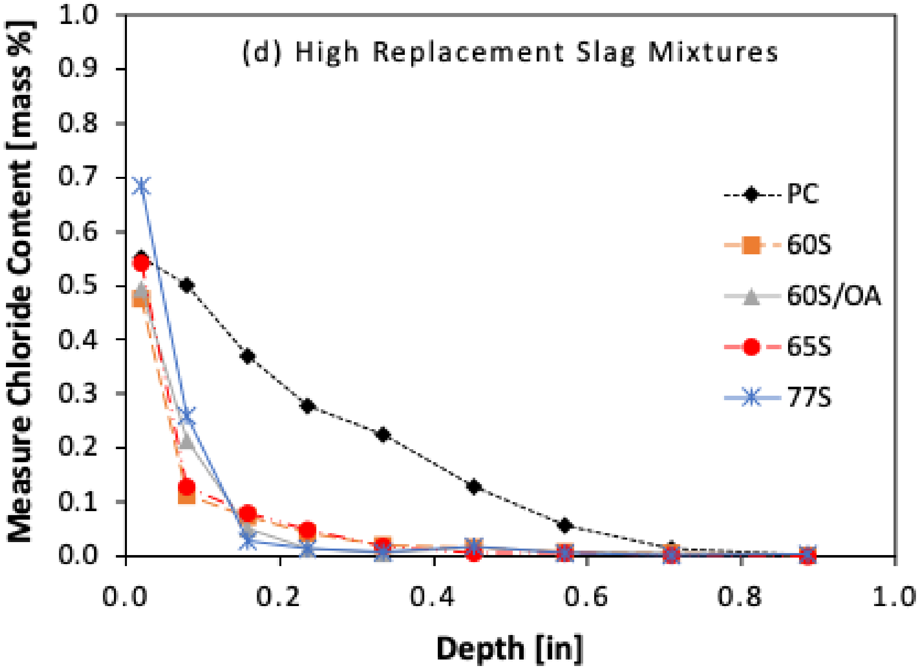

Figure 8. Measured chloride contents at designated depths (high replacement slag mixtures)

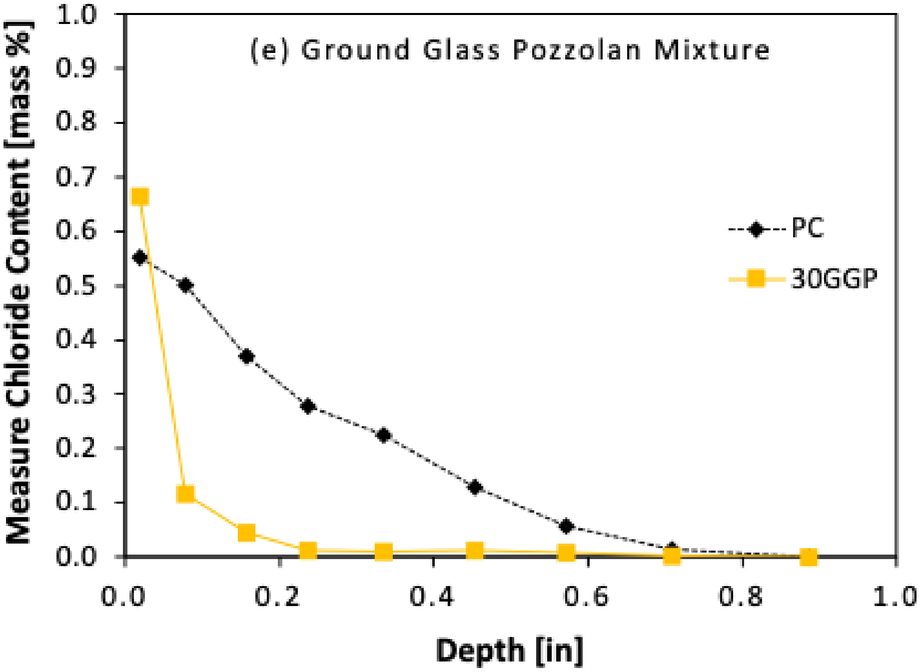

Figure 9. Measured chloride contents at designated depths (ground glass pozzolan mixture)

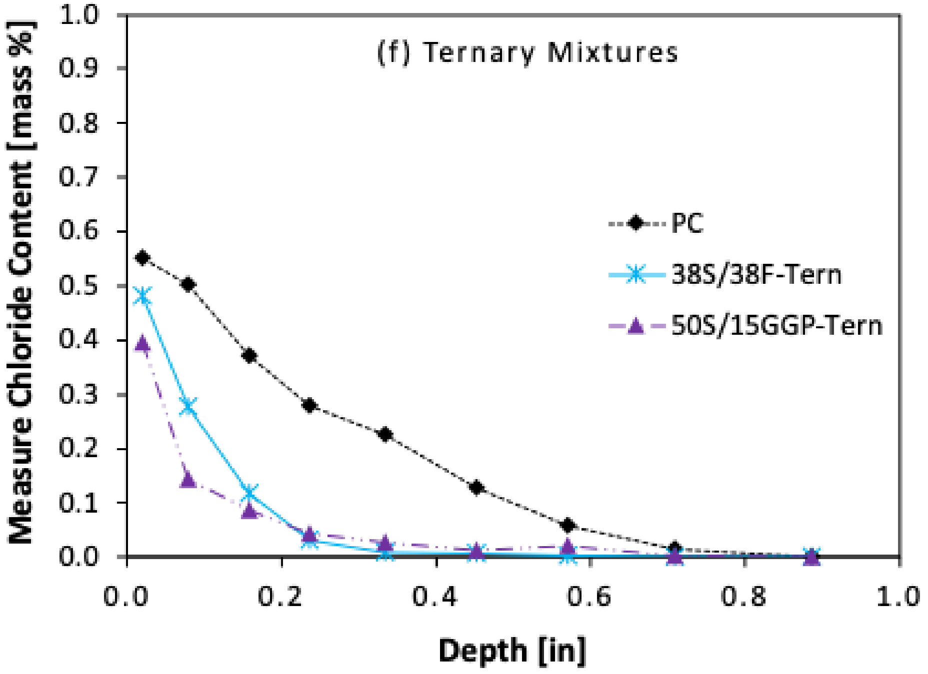

Figure 10. Measured chloride contents at designated depths (ternary mixture)

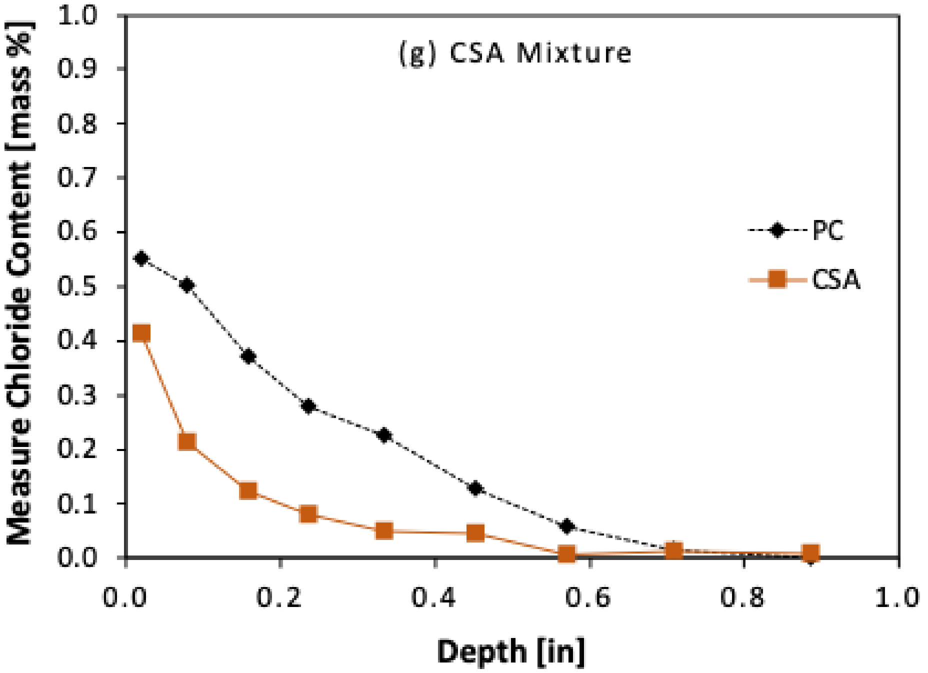

Figure 11. Measured chloride contents at designated depths (CSA mixture)

In addition, as presented in Table 5, the diffusion coefficient of chloride ions in concrete represents the rate at which chlorides move through the concrete matrix. Depending on variables including the temperature, moisture content, degree of saturation, and microstructure of the concrete, this value may vary greatly. While normal-strength Portland cement concrete has a diffusion coefficient ranging from

0.75 to 0.93 in^2/year [30], high-quality concrete with a reduced water-to-cement ratio can achieve values under 0.5 in^2/year [31], offering better resistance to chloride penetration. The diffusion rate for the PC system was calculated at 0.388 in^2/year—approximately half the average value noted earlier, yet nearly an order of magnitude higher than that of all other systems. Among the alternative mixtures, the 30GGP system exhibited the lowest diffusion coefficient at 0.01 in^2/year. Considering the benchmark of 0.5 in^2/year for a "high-quality system," all mixtures evaluated in this study demonstrated strong performance in terms of chloride resistance.

Table 5. Chloride diffusion coefficients of all concrete mixtures

Chloride diffusion coeffient (in^2/year)	**PC**	**30F**	**50S**	**30F/OA**	**50S/OA**	**50S/RCA**	**50S/PLC**	**40F**	**50F**	**40F/OA**	**60S**	**60S/OA**	**77S**	**65S**	**30GGP**	**38S/38F-Tern**	**50S/15GGP-Tern**	**CSA**
	0.388	0.028	0.014	0.025	0.062	0.021	0.015	0.024	0.041	0.025	0.011	0.023	0.017	0.031	0.008	0.045	0.024	0.066

4.2.3 Salt Scaling

The salt scaling profile of all low carbon concrete mixtures are displayed in Figure 12, Figure 13, Figure 14, Figure 15, and Figure 16. Concrete surface damage known as "salt scaling" is brought on by the interaction of freeze-thaw cycles with the penetration of salt solutions, usually from seawater or de-icing agents. When salt-containing water seeps into concrete and freezes, it expands and generates internal pressure leading to surface weakness and microcracks. While salt scaling does not directly cause failure, it accelerates the ingress of aggressive species, such as chlorides, which, in turn, lead to the corrosion of reinforcing steel and a subsequent loss of strength due to internal frost action. Concrete pavements are exposed to deicing salts during certain periods of winter without preventive measures, surface scaling is commonly observed. This type of damage is significantly more severe—approximately ten times more so—than when freeze-thaw cycles occur without the presence of deicing salts [33].

The study adhered to the guidelines outlined in ASTM C672 [29] for testing the scaling resistance of concrete exposed to deicing salts. This involves inspecting the specimens visually at 5-cycle intervals and rating the extent of surface damage from 0 (no scaling) to 5 (severe scaling), providing a standardized measure of the concrete's resistance to salt-induced deterioration. Table 6 summarizes the visual ratings of salt scaling profiles of all concrete mixtures at different cycles. After 50 cycles, three systems—PC, 50S/OA, and 38S/38F-Tern—had no visible damage (rating of 0), while the others received a rating of 1. The 40F system was the only one to show damage before 30 cycles, but only in one specimen. Overall, all systems performed well and showed minimal damage, indicating that they can deemed as resistant to scaling. In addition, while most samples remained intact or suffered only minor damage after 50 freeze-thaw cycles, several mixtures performed particularly well. The 40F/OA, 50F/OA, and 50S/15GGP-Tern samples showed virtually no surface scaling, highlighting their durability. Conversely, the 60S/OA-1 specimen deteriorated more quickly, with visible scaling and pitting evident after only 30 cycles.

Table 6. Salt scaling ratings of concrete mixtures

Specimen (Short ID)	**5 Cycles**	**10 Cycles**	**15 Cycles**	**20 Cycles**	**25 Cycles**	**30 Cycles**	**35 Cycles**	**40 Cycles**	**45 Cycles**	**50 Cycles**	**Average Condition at End**
50S/15GGP-Tern-1	0	0	0	-	-	-	-	-	-	1	**1**
50S/15GGP-Tern-2	0	0	0	-	-	-	-	-	-	1	
CSA-1	0	0	0	0	0	0	0	0	0	1	**1**
CSA-2	0	0	0	0	0	0	0	0	0	1	
40F/OA-1	0	0	0	0	0	0	0	0	0	0	**1**
40F/OA-2	0	0	0	0	0	1	1	1	1	1	
50S/OA-1	0	0	0	0	0	0	0	0	0	0	**0**
50S/OA-2	0	0	0	0	0	0	0	0	0	0	
60S/OA-1	0	0	0	0	0	1	1	1	1	1	**1**
60S/OA-2	0	0	0	0	0	0	0	0	1	1	
30F/OA-1	0	0	0	0	0	0	0	1	1	1	**1**
30F/OA-2	0	0	0	0	0	0	0	0	1	1	
50S/PLC-1	0	0	0	0	0	0	0	1	1	1	**1**
50S/PLC-2	0	0	0	0	0	0	0	0	0	0	
30GGP-1	0	0	0	0	0	0	1	1	1	1	**1**
30GGP-2	0	0	0	0	0	0	0	0	1	1	
50S-1	0	0	0	0	0	0	0	0	1	1	**1**
50S-2	0	0	0	0	0	0	0	0	0	0	
65S-1	0	0	0	0	0	0	0	1	1	1	**1**
65S-2	0	0	0	0	0	0	1	1	1	1	
77S-1	0	0	0	0	0	0	0	0	0	0	**1**
77S-2	0	0	0	0	0	0	0	0	1	1	
50S/RCA-1	0	0	0	0	0	0	1	1	1	1	**1**
50S/RCA-2	0	0	0	0	0	0	0	0	0	0	
38F/38S-Tern-1	0	0	0	0	0	0	0	0	0	0	**0**
38F/38S-Tern-2	0	0	0	0	0	0	0	0	0	0	
PC-1	0	0	0	0	0	0	0	0	0	0	**0**
PC-2	0	0	0	0	0	0	0	0	0	0	
30F-1	0	0	0	0	0	0	0	0	0	1	**1**
30F-2	0	0	0	0	0	0	0	0	0	1	
40F-1	0	0	1	1	1	1	1	1	1	1	**1**
40F-2	0	0	0	0	0	0	0	0	0	1	
60S-1	0	0	0	0	0	0	0	0	0	0	**1**
60S-2	0	0	0	0	0	0	0	0	1	1	
50F-1	0	0	0	0	0	0	0	0	1	1	**1**
50F-2	0	0	0	0	0	0	0	0	1	1	

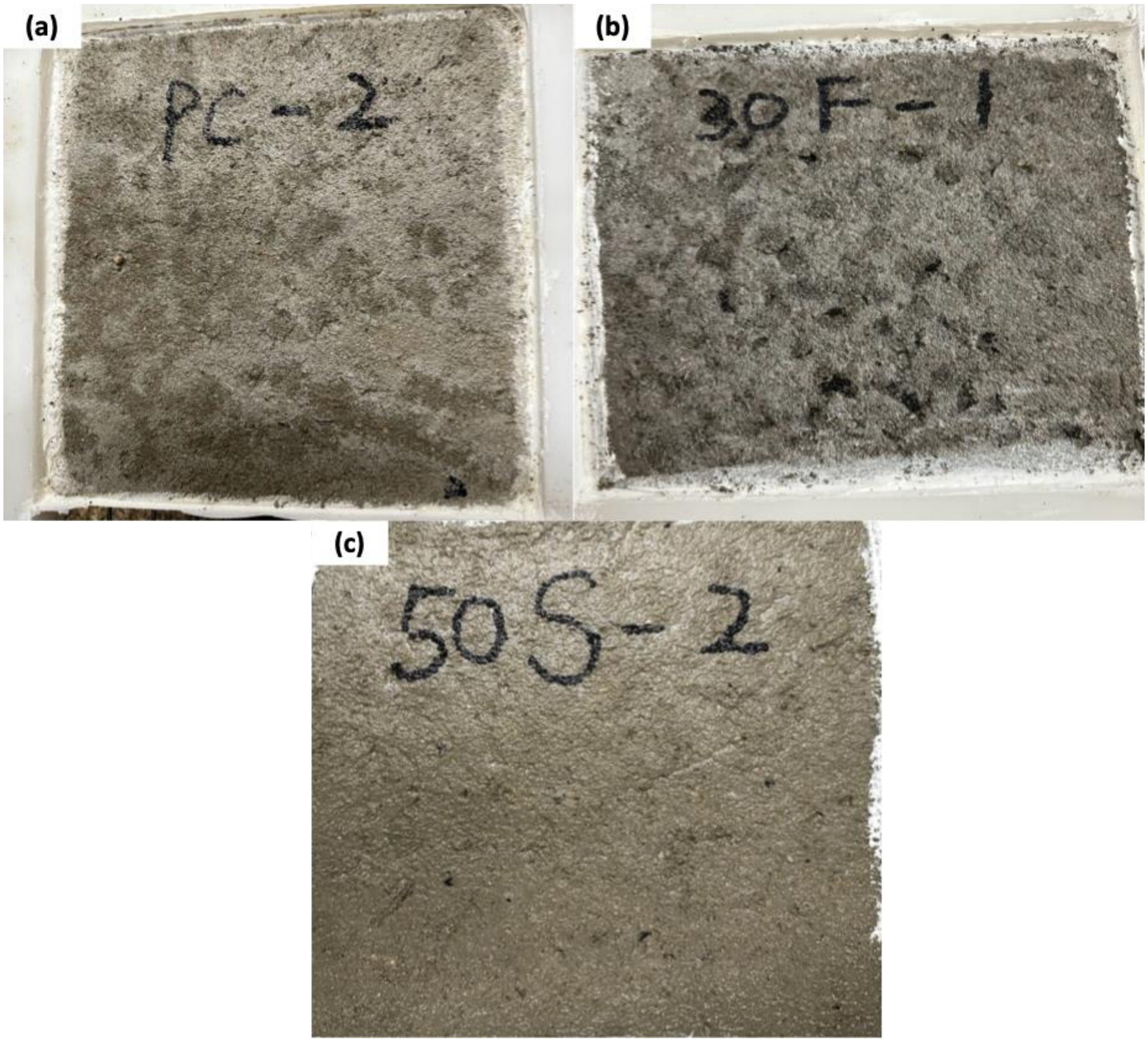

Figure 12. Cycle-50 salt scaling profiles of baseline mixtures: (a) 50S, (b) 30F, and (c) 50S

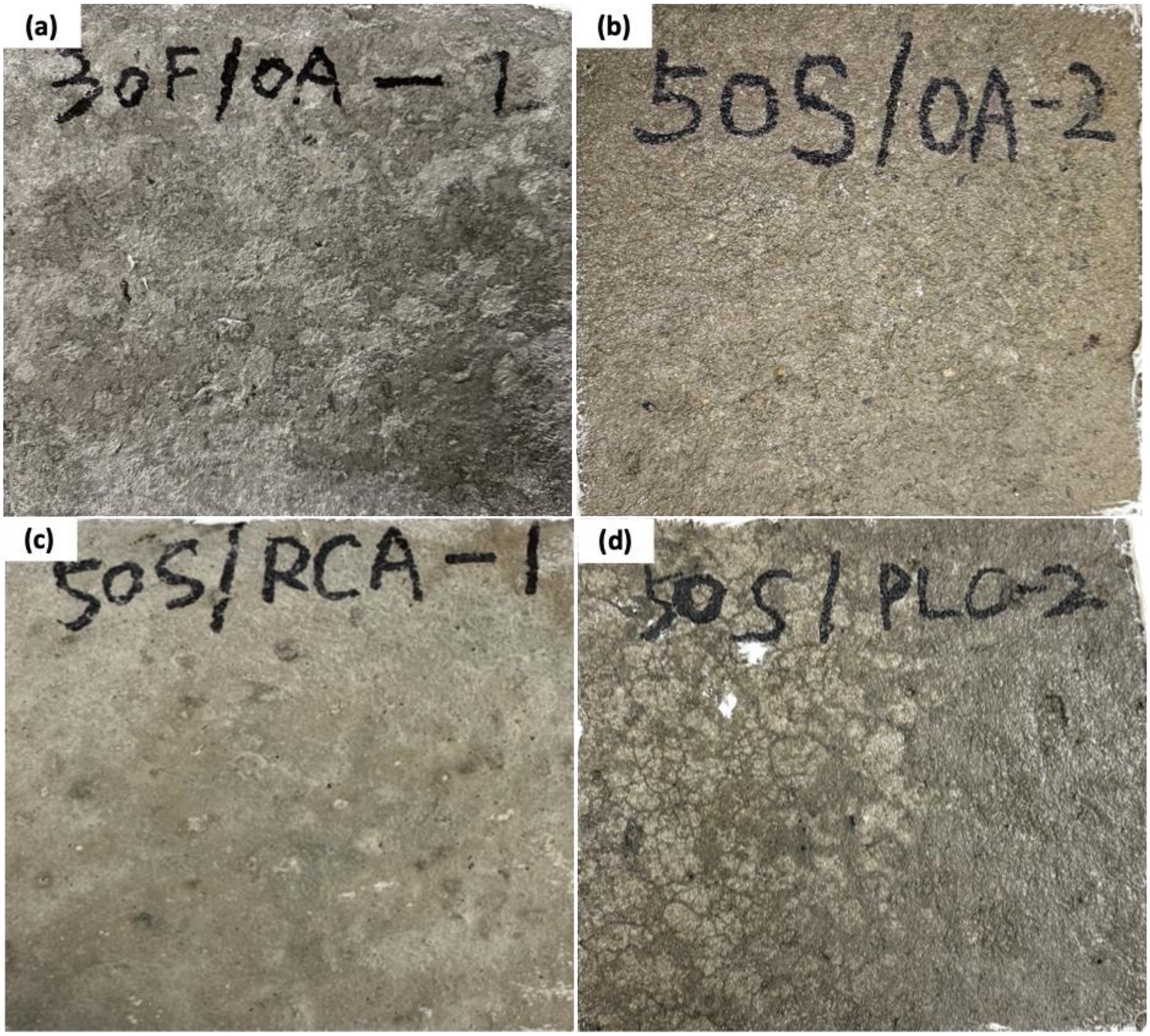

Figure 13. Cycle-50 salt scaling profiles of modified baseline mixtures: (a) 30F/OA, (b) 50S/OA, (c) 50S/RCA, and (d) 50S/PLC

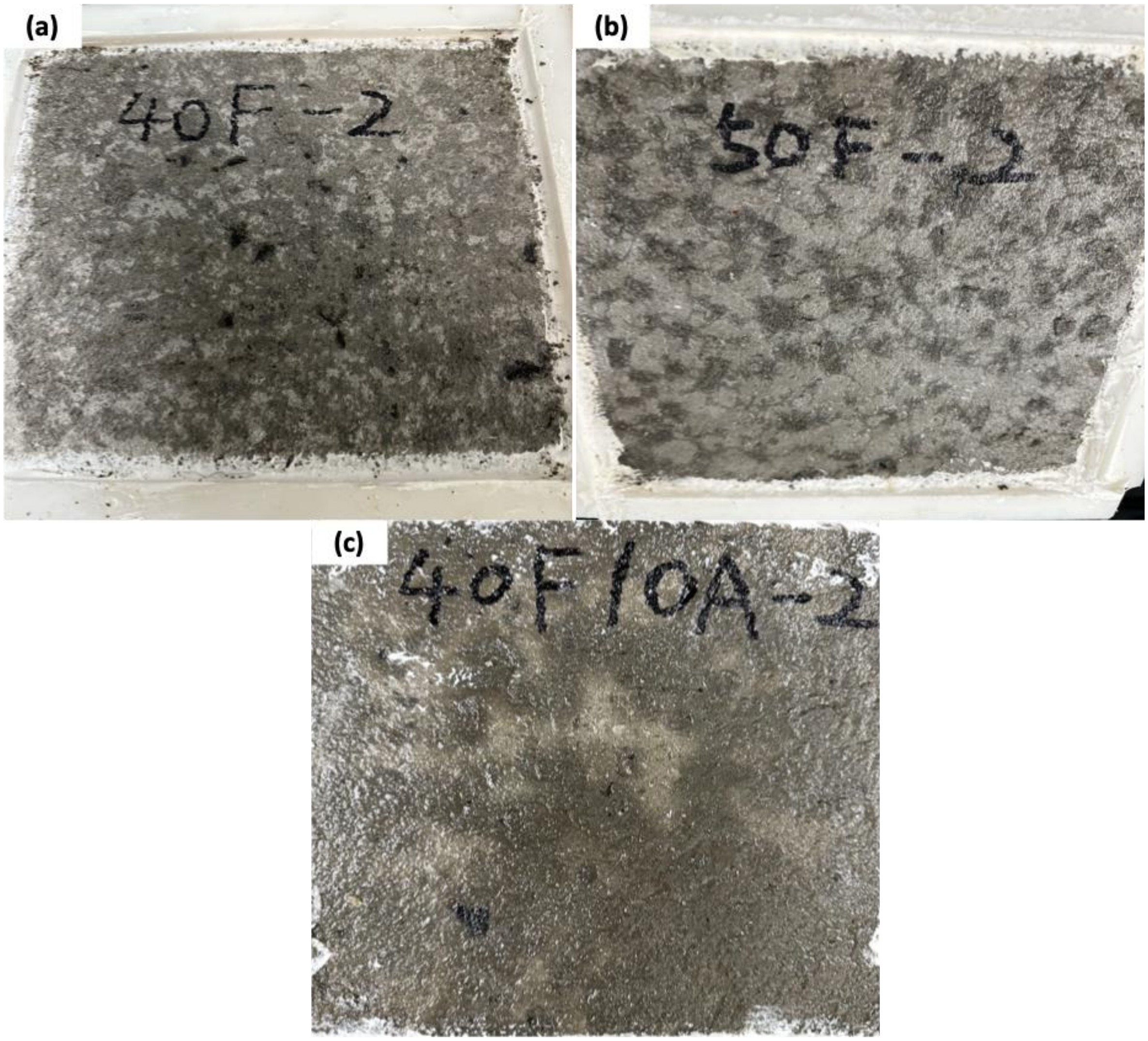

Figure 14. Cycle-50 salt scaling profiles of high replacement fly ash mixtures: (a) 40F, (b) 50F, (c) 40F/OA

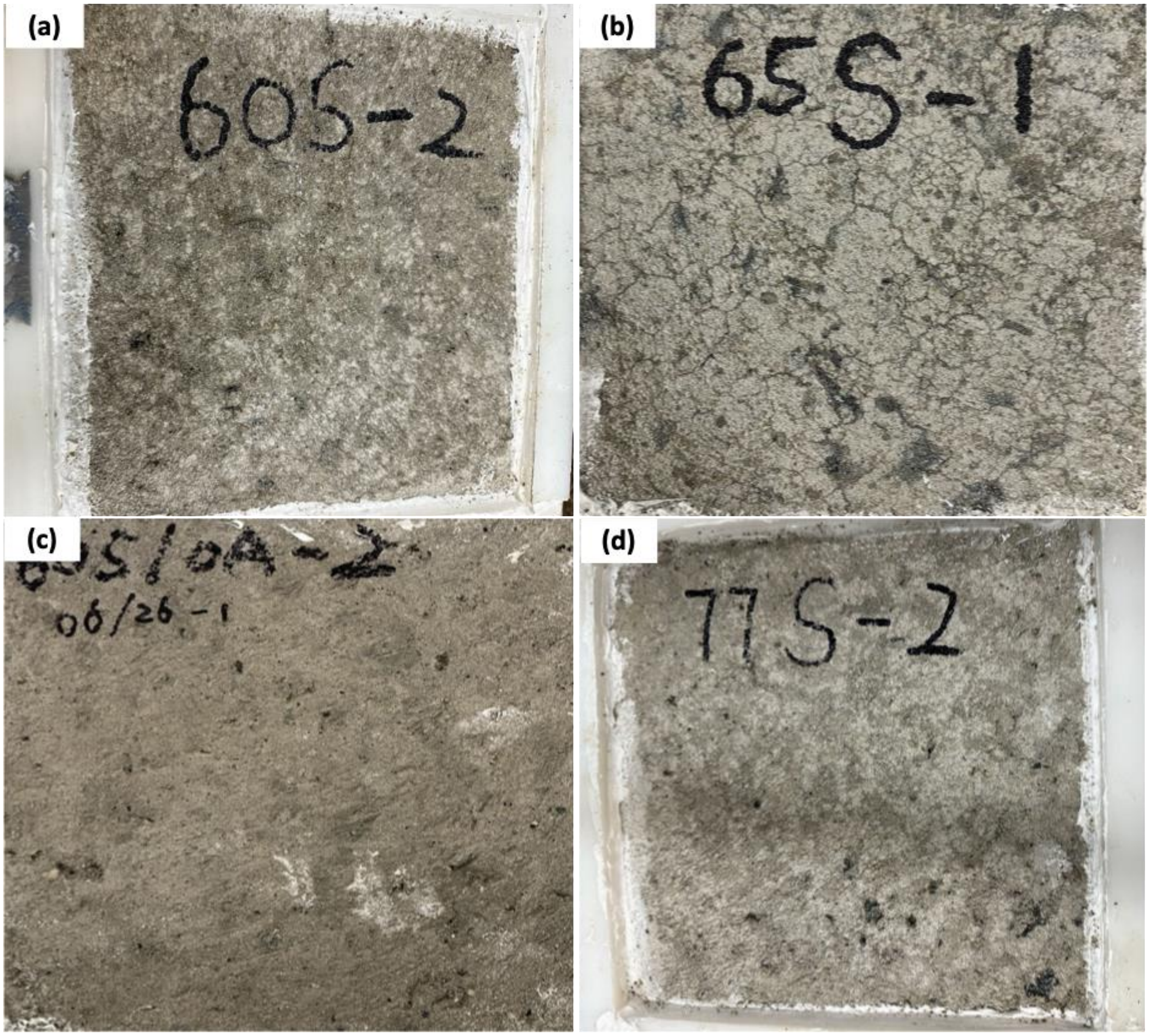

Figure 15. Cycle-50 salt scaling profiles of high replacement slag mixtures: (a) 60S, (b) 65S, (c) 60S/OA, and (d) 77S

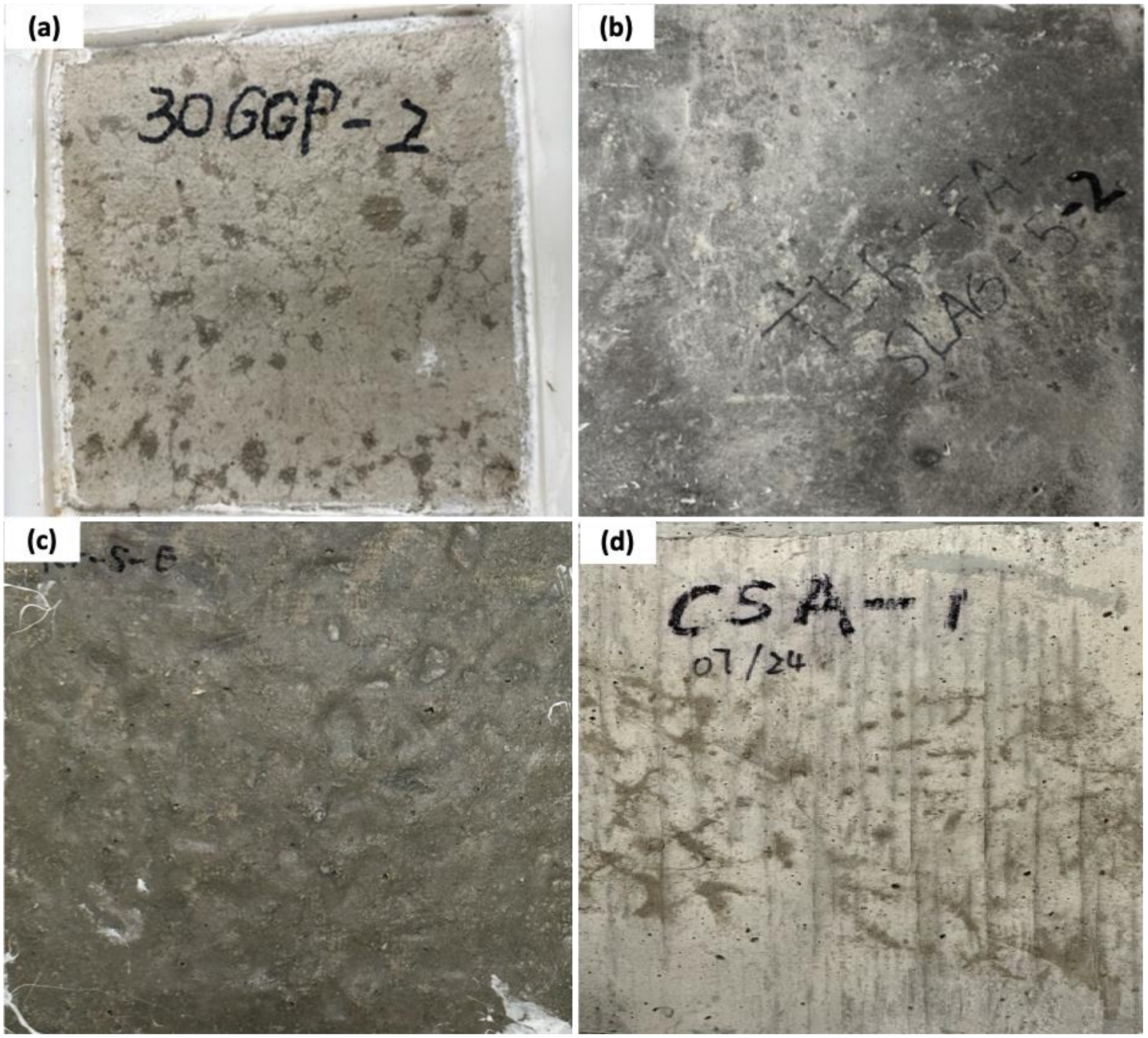

Figure 16. Cycle-50 salt scaling profiles of GGP, ternary, and CSA mixtures: (a) 30GGP, (b) 38F/38S-Tern, (c) 50S/15GGP-Tern, and (d) CSA

5 Analysis of Global Warming Potential of Low Carbon Concrete Mixtures

The Global Warming Potential (GWP) for each concrete mixture was calculated as the total CO_2 equivalent embodied in the mix. The emission factors used for this calculation were sourced from a previous study [34], which also outlined the methodology employed. In addition to absolute GWP values, the relative GWP of each mixture was determined by comparison to the baseline mixtures—PC, 30F, and 50S. These results are summarized in Table 7. Among all mixtures, the baseline PC mixture exhibited the highest GWP, followed closely by the CSA mixture. The lowest GWP was observed in the 77S and 38S/38F-Tern systems. These mixtures contain the least amount of portland cement, which is typically the primary contributor to CO_2 emissions in concrete.

Table 7. Embodied GWP of each concrete mixture and relative performance compared to baseline mixtures

Mixture ID	Concrete GWP, CO_2 eq. (lb of CO_2/yd^3)	Relative Amount of GWP Compared to Baseline PC Mixture (%)	Relative Amount of GWP Compared to Baseline FA Mixture (%)	Relative Amount of GWP Compared to Baseline Slag Mixture (%)
PC	613	100	-	-
FA_30%	487	79	100	112
SLAG_50%	436	71	90	100
FA_30%_OA	399	65	82	91
SLAG_50%_OA	324	53	67	74
SLAG_50%_RCA	430	70	88	99
SLAG_50%_PLC	405	66	83	93
FA_40%	466	76	96	107
FA_50%	423	69	87	97
FA_40%_OA	365	60	75	84
SLAG_60%	357	58	73	82
SLAG_60%_OA	326	53	67	75
SLAG_77%	275	45	57	63
SLAG_65%	323	53	66	74
GGP_30%	386	63	79	89
Ternary_FA_SLAG	307	50	63	70
Ternary_SLAG_GGP	327	53	67	75
CSA	522	85	107	120

6 Recommendations

All systems showed favorable results in salt scaling when compared to published data, indicating that these factors would not affect the decision-making process. At the same time, all mixtures exceeded the normal 28-day strength threshold of 4000 psi for most of the construction activities.

Given the GWP analysis, the 77S system outperformed all mixtures with a concrete GWP of 275 lbs of CO_2/yd^3, which indicates a reduction of carbon footprint by over 55% as compared to PC system (100% portland cement binder mixture). Therefore, we recommend that the 77S system be considered for use in any of the potential pilot program applications. Given high replacement fly ash mixtures, the performance was similar between the 40F and 50F systems, while the 50F system had lower GWP; therefore, we recommend considering the 50F system for use in a small-scale pilot project given the compressive strengths of these systems were relatively lower than other systems. The 60S and 77S mixtures, both characterized by high slag replacement levels, performed similarly in mechanical and durability tests and exhibited comparable chemical profiles. As such, the 60S/OA and 50S/PLC systems are recommended for potential implementation in pilot projects.

We recommend the following systems for use in potential pilot projects, based on their strong performance and potential to reduce embodied carbon: the 77S system, which utilizes a 77% replacement of portland cement with slag; the 50F system, featuring a 50% replacement with fly ash; the 60S/OA system, which combines a 60% slag replacement with an optimized aggregate blend; and the 50S/PLC system, which includes a 50% slag replacement and uses Portland limestone cement (PLC) in place of ordinary portland cement. These systems have demonstrated favorable results across key mechanical and durability tests and present viable, lower-carbon alternatives for future construction projects.

7 Summary

This report presents the results of a study of the durability performance, in particular the chloride resistance, of a range of low carbon concrete mixtures. The team evaluated 18 different concrete systems, with comprehensive testing focused on fresh characteristics (slump, setting time, air content, and fresh density), mechanical performance (compressive strength) and durability properties (chloride ion diffusion and salt scaling resistance).

Overall, the mixtures demonstrated strong performance across several criteria. The 77% slag blend emerged as the most effective, meeting all selective performance benchmarks while offering the lowest carbon cost. Notable alternatives include 40F, 50F, 60S, 65S, 60S/OA, and 50S/PLC, which also showed robust performance.

It is recommended that the 77% slag mixture (77S) be prioritized for implementation in an upcoming pilot project evaluating low-carbon concrete systems. The 50% fly ash mixture (50F) is also suggested for a pilot project, provided the application is not related to pavement construction. Furthermore, the systems incorporating 60% slag with optimized aggregate (60S/OA) and a 50% slag and 50% portland limestone cement (50S/PLC) warrant additional investigation and testing.

The research supports the conclusion that a diverse range of technological solutions can be effectively employed to produce durable, low-carbon concrete. Nonetheless, additional laboratory studies are essential to validate the performance of new combinations, given the current lack of consensus on their synergistic effects.

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