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Addressing Fly Ash Shortage with Limestone Calcined Clay Cement

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Abstract:

Virginia and many other states are experiencing increasing challenges related to the availability of traditional supplementary cementitious materials (SCMs), particularly fly ash. These shortages—with both seasonal and regional variability—threaten the consistency, cost, and performance of concrete used in the Virginia Department of Transportation's (VDOT) infrastructure. At the same time, an increasing emphasis is on reducing the environmental footprint of cement and concrete production, which necessitates the use of SCMs to reduce the global warming potential associated with clinker manufacturing. Calcined clays have emerged as promising alternative SCMs that may address both material supply constraints and sustainability objectives. However, their suitability for VDOT concrete—including effects on fresh properties, strength, durability, and environmental performance—had not been evaluated. This study was initiated to generate the data and guidance needed for informed decision making regarding the adoption of calcined clays in VDOT applications.

This study evaluated limestone calcined clay cement, or LC3—a ternary blended cement typically composed of 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum—and LC2, a cementitious system similar to LC3 produced by replacing 30% of Portland limestone cement (Type IL) with calcined clay. The fresh, mechanical, durability, and shrinkage characteristics of concrete incorporating LC3 and LC2 were assessed and compared with mixtures containing Class F coal ash and slag cement commonly used in VDOT concretes. In addition, the physical, chemical, and reactivity properties of SCMs were characterized, and global warming potential analyses were conducted to quantify the potential environmental benefits associated with incorporating calcined clay. Together, these evaluations provide a comprehensive framework for understanding the suitability of calcined clays for VDOT concrete.

Results showed that calcined clays are substantially more reactive than Class F coal ash and more comparable with slag cement. However, their porous micromorphology and high surface area significantly reduce workability, making admixture selection and dosage critical for field placement. At a 30% dosage, a calcined clay meeting ASTM C618 requirements for Class N pozzolans produced concrete with performance comparable with or better than mixtures containing 30% Class F coal ash, and air entrainment behavior was similar to that of the Type IL control mixture—an advantage over fly ash, which often requires higher air entraining admixture dosages. These findings demonstrate that calcined clays are a viable SCM option that can help alleviate fly ash shortages while maintaining or improving concrete performance. Collectively, this study provides data driven guidance that can improve long term material resilience, reduce the environmental footprint of VDOT concrete, and prepare the agency for the adoption of next generation SCMs and blended cements, including those with calcined clays, which are expected to become more readily available in Virginia in the near future.

FINAL REPORT

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DISCLAIMER

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Virginia and many other states are experiencing increasing challenges related to the availability of traditional supplementary cementitious materials (SCMs), particularly fly ash. These shortages—with both seasonal and regional variability—threaten the consistency, cost, and performance of concrete used in the Virginia Department of Transportation's (VDOT) infrastructure. At the same time, an increasing emphasis is on reducing the environmental footprint of cement and concrete production, which necessitates the use of SCMs to reduce the global warming potential associated with clinker manufacturing. Calcined clays have emerged as promising alternative SCMs that may address both material supply constraints and sustainability objectives. However, their suitability for VDOT concrete—including effects on fresh properties, strength, durability, and environmental performance—had not been evaluated. This study was initiated to generate the data and guidance needed for informed decision-making regarding the adoption of calcined clays in VDOT applications.

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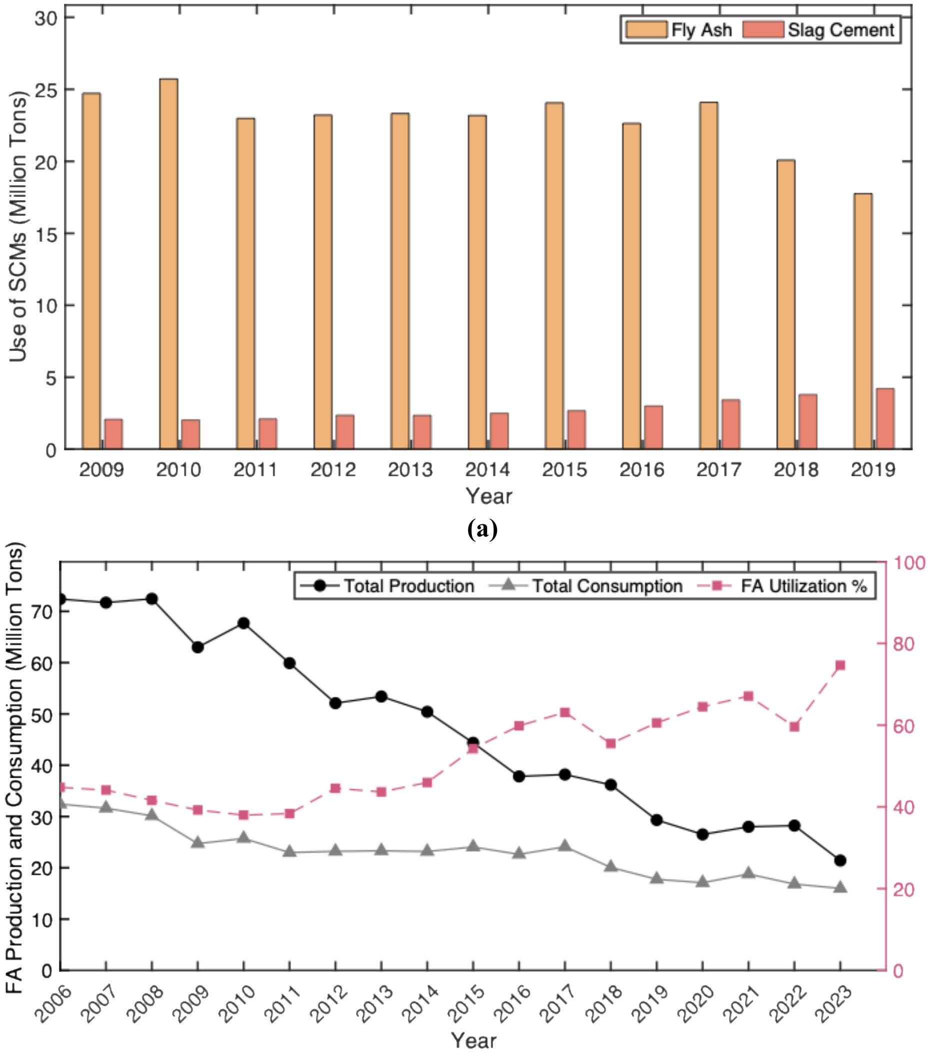
INTRODUCTION

Supplementary cementitious materials (SCMs) play a critical role in modern concrete. SCMs enhance durability by reducing permeability and mitigating harmful reactions while improving long-term mechanical performance. They also help lower the carbon footprint of concrete by reducing clinker demand, the most energy- and emissions-intensive component of cement. In the United States, fly ash (FA) and slag cement (SC) are the most widely used SCMs, with FA historically being the dominant option (Figure 1a) (American Coal Ash Association [ACAA], 2024; Slag Cement Association [SCA], 2022). However, the rapid decline of coal-fired power generation has raised major concerns regarding the long-term availability of FA (Diaz-Loya et al., 2019). As Figure 1b shows, FA production in the United States has steadily declined during the past 15 years leading to a utilization rate of 75% in 2023. This decline has led to seasonal shortages of FA in several regions, a trend corroborated by a 2016 American Association of State Highway and Transportation Officials (AASHTO) survey that found 80% of responding state departments of transportation (DOTs) reported experiencing FA supply challenges (AASHTO, 2016). In response to FA shortages, alternative FA sources like reclaimed coal ashes (RCAs), also referred to as harvested coal ashes, are coming online and being actively used. These materials consist of FA or blends of FA with other coal combustion products (e.g., bottom ash) that are recovered from landfills or impoundments and subsequently processed to meet specification requirements. Importantly, both ASTM C618 (ASTM International, 2023a) and AASHTO M295 (AASHTO, 2021) now permit the use of these RCAs in concrete. In fact, the term *fly ash* is no longer used in these specifications. Instead, the broader term *coal ash* is employed to describe the family of coal combustion products, including freshly produced FA and bottom ash, as well as reclaimed materials. Although RCAs represent an important component of the near- to mid-term solution to the FA shortages (Subedi et al., 2022), their applicability is inherently constrained by the availability of viable landfilled and impounded coal ash resources. As a result, this approach can provide only a temporary supply augmentation and cannot be regarded as a definitive long-term solution. Consequently, a need exists to identify and implement alternative SCMs that can deliver comparable performance and sustainability benefits to FA-blended concrete.



(a)

(b)

Figure 1. (a) FA and Slag Cement Consumption in the United States; (b) Total FA Production and Consumption in the United States and Percentage of FA Utilization from Total Available Production (ACAA, 2024). FA = fly ash; SCMs = supplementary cementitious materials.

Owing to their widespread availability, calcined clays (CCs) have recently emerged as a promising alternative to address the declining supply of FA (Avet et al., 2016). Among naturally occurring clays, kaolinitic clays exhibit the highest pozzolanic potential (Scrivener et al., 2019; Zunino et al., 2020). During thermal activation, kaolinite undergoes dehydroxylation between about 400 and 650°C, forming metakaolin, a highly reactive pozzolanic material with reactivity exceeding that of FA (Scrivener et al., 2019; Zunino et al., 2020). Metakaolin products, derived from high-purity kaolinitic clays, have been commercially available and used in concrete for more than 3 decades and are currently permitted in Virginia Department of Transportation (VDOT) concretes at cement replacement levels of up to 10% (Ding and Li, 2002; VDOT 2020). Despite its proven performance, metakaolin is rarely used in transportation infrastructure because of its high cost. The limited availability of high-purity kaolinitic clay deposits and strong competition from other high-value industries (e.g., cosmetics and ceramics) that rely on the same raw materials primarily drive this cost (Murray, 2006). However, recent research has demonstrated that lower grade kaolinitic clays, containing as little as 40% kaolinite, can be effectively calcined and used as SCMs in concrete, particularly in a ternary blended cement system known as limestone calcined clay cement (LC3) (Scrivener et al., 2019). These clays are abundant and substantially less expensive than high-purity kaolinite, making them well suited for large-scale implementation in concrete (Avet et al., 2016). Importantly, Virginia possesses deposits of low-grade kaolinitic clays that are suitable to produce CCs to use as SCMs.

LC3, first introduced in 2012, is a ternary blended cement typically composed of 50% clinker, 30% CC, 15% limestone, and 5% gypsum by mass (Scrivener et al., 2018). This formulation enables clinker replacement levels sufficient to achieve a 40% reduction in carbon dioxide emissions relative to ordinary Portland cement (OPC) (Scrivener et al., 2018). Under ASTM C595, LC3 is classified as a Type IT cement, specifically IT(P30)(L15), in which the pozzolan fraction consists of CC (ASTM International, 2025). However, with the increasing availability of Portland limestone cement (PLC), containing up to 15% limestone in its composition, similar binder systems can now be produced at the ready-mix plant by partially replacing 30% of the PLC with CC. These systems are commonly referred to as LC2, rather than LC3, because they are proportioned and blended at the concrete batching plant rather than interground at the cement plant. As a result, LC2 systems can exhibit different performance characteristics because the lack of intergrinding and slightly different composition affects the hydration behavior.

In LC3 systems, the pozzolanic reactivity of CC and the filler effect of limestone are key drivers of microstructure densification and strength development (Sharma et al., 2021). In addition, the alumina (i.e., Al_2O_3) supplied by the CC reacts with the carbonates in limestone to form stable carboaluminate phases, further refining the pore network and enhancing mechanical performance (Scrivener et al., 2018; Sharma et al., 2021). These synergistic reactions enable high clinker replacement levels while still achieving a dense, durable cementitious matrix. Compared with OPC, LC3 cements typically exhibit comparable 28-day compressive strength, lower creep, similar autogenous shrinkage, and a finer pore structure (Dhandapani and Santhanam, 2017; Sharma et al., 2021). As a result, LC3 concretes demonstrate reduced permeability, high resistivity, and superior overall durability, with studies reporting significantly extended service life relative to OPC counterparts (Pillai et al., 2019; Sharma et al., 2021). Importantly, LC3 systems also show strong mitigation of alkali-silica reaction (ASR), even with reactive aggregates, providing a critical durability benefit that has traditionally relied on Class F FA (Favier et al., 2015).

CCs used in LC2 and LC3 binder systems offer a promising pathway for addressing FA shortages while maintaining durability, mitigating alkali-silica reaction, and reducing clinker content and associated greenhouse gas emissions. However, limited agency experience with these materials creates practical risks if they are adopted without VDOT-specific performance data. Because most published LC2 and LC3 studies reflect non-U.S. materials and different construction practices, targeted testing using cementitious materials and mixture designs representative of VDOT concrete is needed to quantify fresh properties, strength development, durability indicators, shrinkage, and environmental impacts and to translate findings into implementable guidance. Accordingly, this research aimed to reduce uncertainty, support specification development, and ensure that any future use of CCs improves supply resilience and sustainability without compromising constructability or long-term performance of VDOT infrastructure. Virginia possesses extensive clay and limestone deposits, making it particularly well suited for regional implementation (Virginia Energy, 2022a, 2022b). Accordingly, evaluating these cementitious systems is highly relevant to VDOT and supports their broader potential implementation in future infrastructure applications. This relevance is further underscored by Roanoke Cement—Virginia's only cement producer—planning to produce and incorporate CC materials sourced from within Virginia in a future LC3 product (Titan America, 2025).

PURPOSE AND SCOPE

The purpose of this study was to evaluate LC2 and LC3 systems as viable alternatives to conventional FA- and SC-based cementitious binder systems for concrete applications in Virginia. This work aims to establish a comprehensive understanding of the performance and the environmental benefits of concrete incorporating CC. The specific objectives of the study were to:

- Characterize the physical, chemical, and reactivity properties of CCs.
- Assess the fresh, hardened, and durability properties of VDOT Class A4 General concrete incorporating LC2 and LC3 systems.
- Quantify the greenhouse gas emissions associated with LC2 and LC3 concrete materials.

METHODS

Overview

This research project consists of four tasks to achieve the main research objective. The following lists the research tasks, which are described in detail in subsequent sections:

1. Literature review.
2. Characterization of cementitious materials.
3. Evaluation of the properties of concrete incorporating LC2 and LC3 systems.
4. Environmental impact assessment.

Literature Review

A comprehensive literature review on LC2 and LC3 systems was conducted to support and guide the research activities in this project. In addition, studies related to life-cycle assessment (LCA) of low-carbon concrete materials were reviewed to establish the current state of knowledge on environmental and cost performance.

Characterization of Cementitious Materials

Materials

A commercial Type IL cement, composed of approximately 14.4% limestone and 4% gypsum, was employed in this study. CCs from two U.S. sources, designated as CC-1 and CC-2, were investigated. CC-1 was received as a ready-to-use powder from the manufacturer, whereas CC-2 was supplied in an unground state and subsequently processed in the laboratory. Specifically, CC-2 underwent ball milling for 165 minutes using a ball mill grinder, a duration determined to optimize the powder yield and achieve the targeted particle size distribution. The resultant CC-2 powder was collected after passing through a No. 200 sieve (75 µm). In addition to the CCs, a RCA meeting ASTM C618 Class F coal ash requirements and an ASTM C989-compliant Grade 120 SC were included in the study for comparative assessment. The specific gravities of PLC, CC-1, CC-2, RCA, and SC were 3.07, 2.74, 2.90, 2.34, and 2.82, respectively. Figure 2 presents photographs of the cement and SCMs considered in this study.

Figure 2. Cement and Supplementary Cementitious Materials Considered in this Study

X-Ray Fluorescence Spectrometry

X-ray fluorescence spectrometry analysis was performed to identify the chemical composition of the cement and SCMs considered in this study. The measurements were taken using an X-ray fluorescence spectrometer equipped with a silver anode X-ray tube. The spectrometer was operated at 40 kV and 40 mA.

Particle Size Distribution

The particle size distribution of the cementitious materials was measured using a laser diffraction particle size analyzer. This technique enables precise quantification of particle sizes across a wide range, allowing assessment of the distribution curve, mean particle diameter, and uniformity of the samples.

Scanning Electron Microscopy

The surface morphology of cementitious materials was analyzed using a FEI Quanta 650 scanning electron microscope. To enhance conductivity and improve image contrast, a thin layer of gold was sputter-coated onto the samples under vacuum conditions before imaging.

Rapid, Relevant, and Reliable Reactivity Test

To evaluate the reactivity of the selected SCMs, the rapid, relevant, and reliable (R3) reactivity test was conducted in accordance with ASTM C1897-20 (ASTM International, 2020a), employing both methods A and B. In the R3 reactivity test, a paste containing the evaluated SCM is prepared together with a blend of calcium hydroxide, calcium carbonate, potassium sulfate, and potassium hydroxide, combined in proportions that simulate the chemical environment of a Portland cement system. In Method A, an isothermal calorimeter is used to monitor the heat evolution during hydration of the paste at 40°C ± 2°C during a 7-day period. Method B involved quantifying the amount of chemically bound water in the paste after curing under identical conditions (40°C ± 2°C for 7 days), providing complementary insights into the hydration process and reactivity level of each SCM. For each SCM, two samples were prepared and tested.

Strength Activity Index

The strength activity index (SAI) of the SCMs in this study was assessed according to ASTM C311 (ASTM International, 2023b), with a modification: a fixed water-to-binder (w/b) ratio was maintained rather than adjusting w/b to achieve constant flow. Although ASTM C311 typically requires changes in w/b to ensure consistent flow, such adjustments can introduce ambiguity by affecting porosity and, consequently, compressive strength. To avoid this confounding variable and facilitate straightforward interpretation, a constant w/b of 0.484 was adopted. In addition, a sand-to-binder ratio of 2.75 was applied in all mixtures, as the standard specifies. A commercially available ASTM C778 graded sand was used to prepare the mortar samples for the SAI test (ASTM International, 2022c). As the standard specifies, 20% of the PLC was substituted with the respective SCM. SAI measurements were performed at both 7 and

28 days of curing in saturated limewater. For fair comparison, the SAI of SC was also determined using the same methodology, although this result is intended only for experimental uniformity and does not formally meet ASTM C311 compliance.

Evaluation of the Properties of Concrete Incorporating LC2 and LC3 Systems

Concrete Mixture Design and Sample Preparation

Six concrete mixtures were designed to evaluate the influence of cementitious binder systems on concrete performance. Figure 3 illustrates the evaluated binder systems. In concrete materials, only CC-1 was used because it was commercially available as a ready-to-use powder. To produce the laboratory LC3 formulation, the CC was blended with PLC, limestone powder (median particle size of 4.5 µm and specific gravity of 2.70), and reagent-grade gypsum (calcium sulfate dihydrate with specific gravity of 2.32) in proportions of 50% clinker, 30% CC, 15% limestone powder, and 5% gypsum by mass. To produce LC2 systems, CC was used to replace 30% and 50% of PLC by mass. The 30% CC replacement (IL-30CC) was selected to produce an LC2 system comparable with the standard LC3 composition, whereas the 50% replacement (IL-50CC) was intended to explore the performance of a more sustainable LC2 system with a reduced clinker content. By comparison, cementitious binder systems incorporating RCA and SC were also prepared at replacement levels of 30% and 50%, respectively, values corresponding to the maximum allowable dosages for these SCMs according to the VDOT *Road and Bridge Specifications* (VDOT, 2020). Accordingly, concretes incorporating LC2 (IL-30CC and IL-50CC) and LC3 binder systems could be compared with those using RCA (IL-30RCA) and SC (IL-50SC), which VDOT commonly uses. In addition, a mixture containing only Type IL cement (IL), served as the control.

In line with VDOT's (2020) *Road and Bridge Specifications*, each mixture employed the maximum w/b of 0.45 and a nominal maximum aggregate size of 1 inch (ASTM C33 #57 granite coarse aggregate). The sand used was natural silica concrete sand meeting the requirements of ASTM C33 (ASTM International, 2024a). The saturated surface dry specific gravities of the coarse and fine aggregates were 2.80 and 2.65, respectively. The cementitious content of the mixtures was 635 ± 6 lb/yd^3, with the slight variation (less than 1%) resulting from volumetric adjustments associated with differences in the specific gravity of the cementitious materials. This result occurred because all mixtures were designed with a fixed w/b of 0.45, as previously mentioned, and aggregate-to-binder ratio of 4.65. It is important to highlight that VDOT specifications for Class A4 concrete require a minimum cementitious content of 635 lb/yd^3. However, as part of an ongoing Virginia Transportation Research Council (VTRC) project (Project No. 124301), efforts are underway to define new, lower minimum cementitious content limits for VDOT concrete mixtures. A target slump of 2 to 4 inches and an air content of 6.5 ± 1.5% were established for workability and durability performance, per VDOT's specifications. To achieve these targets, a dual water reducer and workability retaining admixture (WR), as well as a polycarboxylate-based high-range water reducer (HRWR), were incorporated to adjust slump, and an air-entraining admixture (AEA) was used to regulate air content. Table 1 provides the detailed mixture proportions.

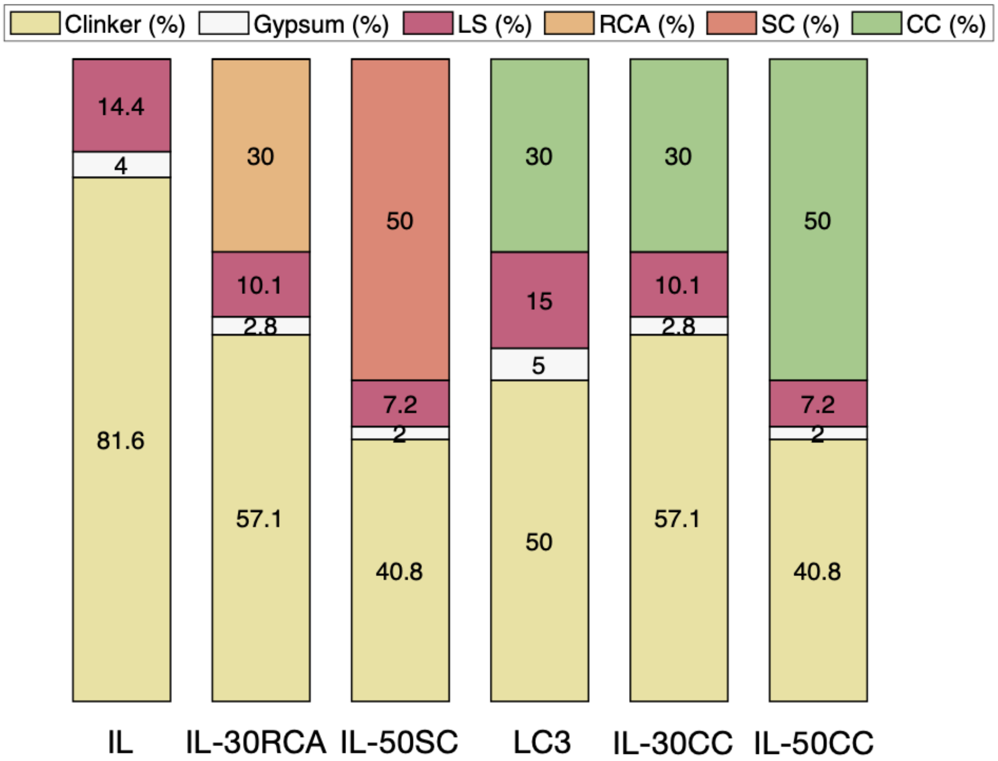


Figure 3. Cementitious Binder Systems Evaluated. CC = calcined clay; IL = Type IL cement; LS = limestone powder; RCA = reclaimed coal ash (Class F); SC = slag cement.

Table 1. Mixture Proportions of Concrete Mixtures

Mix ID	**Cementitious Materials (lb/yd^3)**					**Aggregate (lb/yd^3)**		**Water (lb/yd^3)**	**Admixtures (fl oz/100 lbs of cementitious)**		
	PLC	**CC**	**RCA**	**SC**	**LC3**	**Coarse**	**Fine**		**AEA**	**WR**	**HRWR**
IL	636	0	0	0	0	1788	1171	286	0.45	2.28	0.58
IL-30RCA	440	0	189	0	0	1768	1158	282	0.82	0.19	0.00
IL-50SC	316	0	0	316	0	1779	1165	284	0.45	2.28	0.20
IL-30CC	443	190	0	0	0	1779	1165	284	0.45	2.28	3.40
LC3	0	0	0	0	636	1787	1170	285	0.45	2.28	3.28
IL-50CC	315	315	0	0	0	1771	1160	283	0.45	2.28	8.18

AEA = air-entraining admixture; CC = calcined clay; HRWR = high-range water reducer; LC3 = limestone calcined clay cement; PLC = Portland limestone cement; RCA = reclaimed coal ash (Class F); SC = slag cement; WR = water reducer and workability retaining admixture.

Concrete was mixed in accordance with ASTM C192 using a 13-gallon pan mixer (ASTM International, 2024b). Coarse aggregate and one-half of the mixing water (containing dissolved AEA) were added prior to mixer rotation. Subsequently, sand, cementitious materials, and the remaining mixing water were introduced sequentially. After the water addition, the mixture was blended for 3 minutes, allowed to rest for 3 minutes, and then mixed for an additional 2 minutes following the incorporation of WR and HRWR to reach the target slump. For all concrete materials produced, fresh, hardened, and durability properties were assessed.

Fresh Properties

Fresh concrete properties, including air content and unit weight, were measured following ASTM C231and ASTM C138 (ASTM International, 2023c, 2024c), respectively. The concrete slump was evaluated per ASTM C143 (ASTM International, 2023d).

Compressive Strength

Compressive strength tests were performed on 4 × 8 inch cylindrical specimens at 7, 28, 90, and 196 days, following ASTM C39 (ASTM International, 2024d). Three specimens were tested at each testing age. All specimens were moist-cured in a moisture room in accordance with ASTM C511 until testing (ASTM International, 2021).

Elastic Modulus

Elastic modulus tests were performed on 4 × 8 inch cylindrical specimens at 28, 90, and 196 days following ASTM C469 (ASTM International, 2022a). Three specimens were tested at each testing age. All specimens were moist-cured in a moisture room in accordance with ASTM C511 until testing (ASTM International, 2021).

Electrical Surface Resistivity

Surface resistivity was measured on cylindrical specimens at 7, 28, 56, 90, and 196 days in accordance with AASHTO T358 (AASHTO, 2023). Three specimens were tested at each testing age. All specimens were cured in limewater in accordance with ASTM C511 until testing (ASTM International, 2021).

Chloride Ion Penetration

Chloride ion penetration was evaluated following the rapid chloride permeability test as per ASTM C1202 at 28 and 196 days (ASTM International, 2022b). Two 4 × 8 inch cylindrical specimens were cured in limewater in accordance with ASTM C511 until the testing age (ASTM International, 2021). Afterward, 2-inch slices were cut from the top section of each cylinder, and samples were conditioned as specified in ASTM C1202 prior to testing (ASTM International, 2022b).

Sorptivity

The water permeability of concrete, specifically the initial and secondary water sorptivity (i.e., rate of water absorption), was determined in accordance with ASTM C1585 after 196 days of curing (ASTM International, 2020b). Three 4 × 8 inch cylindrical specimens were cured in limewater in accordance with ASTM C511 until the testing age (ASTM International, 2021). Afterward, 2-inch slices were cut and conditioned at 122 ± 3°F and 80 ± 3% relative humidity for 3 days prior to testing following ASTM C1585. For the sorptivity test, the lateral surfaces were sealed with aluminum tape, leaving the top surface exposed.

Non-Steady-State Chloride Migration Test

The non-steady-state chloride migration test was conducted in accordance with NT Build 492 after 196 days of curing (NT Build, 1999). This test measures the chloride migration coefficient, which reflects the rate at which chloride ions move through concrete under an external electric field. Unlike the rapid chloride permeability test, it does not rely solely on electrical measurements. Instead, it directly quantifies chloride transport by measuring the actual depth of chloride penetration. Three 4 × 8 inch cylindrical specimens were cured in limewater in accordance with ASTM C511 until the testing age (ASTM International, 2021). Next, 2-inch slices were cut and conditioned following NT Build 492 prior to testing. After testing, specimens were split and sprayed with silver nitrate solution. The chloride penetration depth was taken as the visible boundary of white silver chloride precipitation.

Drying Shrinkage

Drying shrinkage was measured on 3 × 3 × 11.25 inch prism specimens according to ASTM C157 (ASTM International, 2024e). Three specimens were cast. Samples were demolded at 23.5 ± 0.5 h, soaked in lime-saturated water for at least 30 minutes, and their initial comparator readings were recorded. After 7 days of limewater curing at 73 ± 3°F, a second reading was taken. Specimens were then stored in the drying room (73 ± 3°F, 50 ± 4% relative humidity). Comparator readings were recorded at 4, 7, 14, and 28 days and at 8, 16, 32, and 48 weeks of drying. Table 2 summarizes the experimental program for the concrete mixtures evaluated in this study, including fresh, hardened, and durability properties.

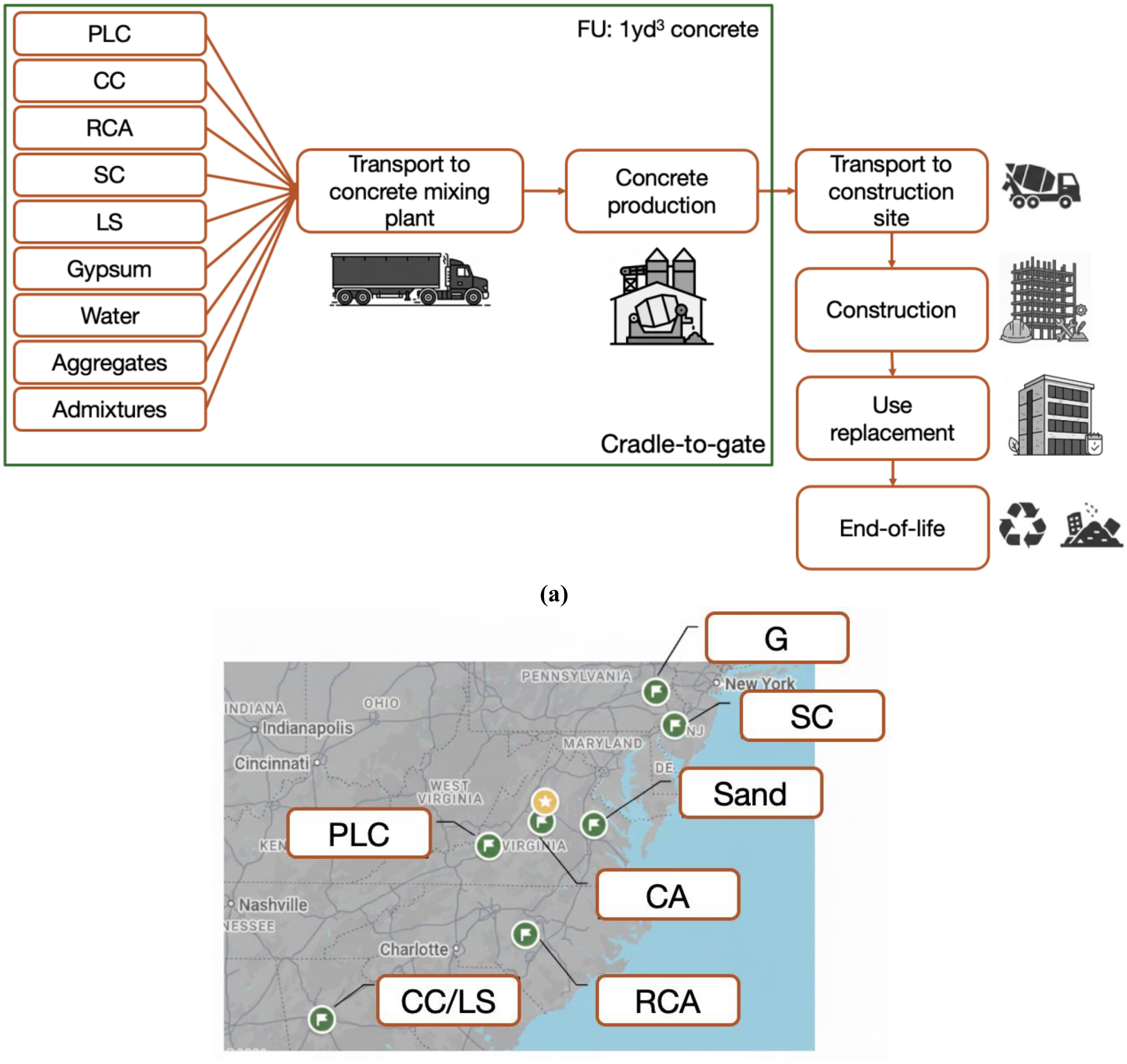
Table 2. Experimental Program for Concrete Mixtures

Property	Test	Specimen Size/Geometry	Curing	No. of Specimens and Testing Age
Slump	ASTM C143	N/A	N/A	N/A
Air Content	ASTM C231	N/A	N/A	N/A
Unit Weight	ASTM C138	N/A	N/A	N/A
Compressive Strength	ASTM C39	4×8 in. cylinder	Moist room	3 each at 7, 28, 90, and 196 days
Modulus of Elasticity	ASTM C469	4×8 in. cylinder	Moist room	3 each at 28 and 90 days
Surface Resistivity	AASHTO T358	4×8 in. cylinder	Limewater	3 each at 7, 28, 90, and 196 days
Chloride Permeability	ASTM C1202	4×2 in. slice from 4×8 in. cylinder	Limewater	2 each at 28 and 196 days
Chloride Migration Coefficient	NT Build 492	4×2 in. slice from 4×8 in. cylinder	Limewater	3 each at 196 days
Sorptivity	ASTM C1585	4×2 in. slice from 4×8 in. cylinder	Limewater	3 each at 196 days
Length change	ASTM C157	3×3×11.25 in. prism	Limewater for 7 days, then dry room	3 each at 4, 7, 14, 28, 56, 90, and 120 days of drying

N/A = not applicable.

Environmental Impact Assessment

LCA evaluates the environmental impacts of a product, process, or system throughout its life cycle, from raw material extraction and manufacturing to transportation, use, and end-of-life stages (Santos et al., 2021). An LCA of the concrete mixtures presented in Table 1 was conducted according to the International Organization for Standardization (ISO) 14040 (ISO, 2006). This analysis aimed to compute the carbon emissions and energy consumption of selected mixtures, examining the influence of different SCMs on environmental impacts. The system boundary was "cradle-to-gate," encompassing processes from raw material extraction to concrete manufacturing (Figure 4a). The concrete mixture is presumed to be prepared at a concrete mixing plant in Charlottesville, Virginia, as the flag marker in Figure 4b indicates. The raw materials are transported from the manufacturing site to the mixing plant via truck. The declared unit was 1 yd^3 concrete mixture.



(a)

(b)

Figure 4. (a) Life-Cycle Assessment System Boundary; (b) Material Source Locations with Flag Markers Indicating Origins and a Star Marker Representing the Manufacturing Site. CA = coarse aggregate; CC = calcined clay; FU = functional unit; G = gypsum; LS = limestone powder; PLC = Portland limestone cement; RCA = reclaimed coal ash (Class F); SC = slag cement.

Table 3 summarizes the life-cycle inventory data sources for the raw materials and processes involved in concrete mixtures. The FA used in this study is reclaimed FA, recovered from landfill FA through a dry process (Baker et al., 2019). Consequently, the associated environmental impacts primarily stem from the electricity and gas consumed during the reclamation process. The life-cycle inventory of concrete production includes the effects associated with operational energy consumption, such as electricity and natural gas usage. Global warming potential (GWP) and cumulative energy demand (CED) were calculated using openLCA with TRACI 2.1 and CML-IA Baseline method, respectively.

Table 3. Carbon Emission and Energy Consumption and Ingredient Data Sources

A1 Stage: Raw Materials Supply			
Materials	**LCI Data Source**	**Geography**	**Reference**
PLC	EPD from Roanoke Cement Company	USA	(Titan Cement, 2023)
Calcined clay	Self-declaration report from manufacturer	USA	
RCA	Only electricity for reclamation process is considered, data from scientific literature	USA	(Hafez et al., 2020)
Slag cement	EPD from Slag Cement Association (Industrial average)	North America	(SCA, 2021)
LS	Ecoinvent 3.4: Limestone, at mine	USA	(Ecoinvent, 2017)
Gypsum	Ecoinvent 3.4: Gypsum, at mine	USA	
Water	Ecoinvent 3.4: Tap water, at user	USA	
Sand	Ecoinvent 3.4: Sand, at mine	USA	
CA	Ecoinvent 3.4: Gravel, crushed	USA	
HRWR	EPD from European Federation of Concrete Admixtures Associations (Industrial average)	EU	(EFCA, 2021)
A2 Stage: Transportation			
Process	**LCI Data Source**	**Geography**	**Reference**
Road	USLCI 2024: Transport, combination truck, short-haul, diesel powered/tkm/RNA	USA	(NREL, 2024)
A3 Stage: Manufacturing			
Process	**LCI Data Source**	**Geography**	**Reference**
Concrete production	Industry-average values from NRMCA LCA report	USA	(NRMCA, 2020)

CA = coarse aggregate; EPD = environmental product declaration; HRWR = high-range water reducer; LCA = life-cycle assessment; LCI = life-cycle inventory; LS = limestone powder; NRMCA = National Ready Mixed Concrete Association; PLC = Portland limestone cement; RCA = reclaimed coal ash (Class F).

RESULTS AND DISCUSSION

Literature Review

In this section, the literature review on the use of CCs in concrete is provided first. Then, the existing LCA methodologies for concrete materials are surveyed and discussed.

Calcined Clays as Supplementary Cementitious Materials

The utilization of CC as an SCM in concrete represents a promising pathway for addressing the scarcity of FA and reducing the carbon footprint of cement-based construction. CCs, particularly those rich in kaolinite, are widely available and, upon suitable thermal activation, yield highly reactive amorphous aluminosilicates (Zunino et al., 2020). The formation of metakaolin during calcination imparts significant pozzolanic reactivity, enabling the clay to participate in cement hydration by reacting with calcium hydroxide and generating additional calcium silicate hydrates (Jafari and Rajabipour, 2021). This chemical transformation results in improved mechanical properties and durability in blended systems, as demonstrated by extensive benchmarking across a wide range of clay grades (Scrivener et al., 2019). In addition, even clays with moderate kaolinite content have been shown to provide sufficient pozzolanicity for practical applications, facilitating broader deployment than previously possible with high-purity metakaolin alone (Cancio Diaz et al., 2019).

Several factors govern the optimization of CC properties: the mineralogical composition of the raw clay, the calcination temperature, and the presence of secondary phases (Danner et al., 2018). Thermogravimetric analysis is effective in quantifying kaolinite content (Lorentz, 2020), whereas the R3 reactivity test has emerged as a robust method for assessing the pozzolanic capacity of CCs (Pinheiro et al., 2023). Studies suggest that the optimal calcination temperature for kaolinitic clays typically ranges between 700 and 850°C, where full dehydroxylation is achieved, but physical coarsening and agglomeration are minimized, maintaining high reactivity (Jafari and Rajabipour, 2021; Scrivener et al., 2019; Zunino, 2020). Furthermore, industrial flash calcination slightly enhances specific surface area and early reactivity compared with static kiln methods, although both approaches can yield high-performance CCs if process parameters are well controlled (Scrivener et al., 2019). The presence of illite and quartz, that is, secondary mineral phases, can slightly reduce early reactivity but does not significantly impede long-term strength development (Danner et al., 2018).

When incorporated into LC3, CC functions synergistically with limestone to deliver enhanced performance and significant savings (Zunino et al., 2020). LC3 is a ternary blended cement system in which clinker is partially replaced by CC and limestone, a combination that allows clinker substitution levels up to 50%. The widely investigated formulation typically consists of 50% clinker, 30% CC, and 15% limestone. Mechanical testing demonstrates that LC3 with 50% clinker replacement can reach OPC performance (Dhandapani et al., 2018; Scrivener et al., 2019). This performance holds even in systems employing moderate-grade CCs. For instance, mortars using clay with at least 40% calcined kaolinite content are capable of reaching comparable strengths to plain OPC from 7 days and onward, and lower grade metakaolin systems generally show comparable mechanical performance to OPC (Sun et al., 2024). The resultant blended cement demonstrates a pronounced refinement of pore structure, producing a more refined and less connected microstructure than OPC (Dhandapani et al., 2018). The synergistic reaction between the CC and limestone actively aids in pore refinement (Sun et al., 2024), resulting in an increase in gel pores and a reduction in coarse pores (Zuninio, 2020). This microstructural evolution is critical as the denser structure leads to lower permeability and thus more durable concrete. This durability is evident in the system's outstanding resistance to chloride ingress, with the chloride diffusion coefficient reported to be significantly lower (about 5 to 10 times) compared with OPC concrete (Dhandapani et al., 2024).

Rheological behavior is a critical consideration for the successful field application of CC cements (Aramburo et al., 2019). The incorporation of CC significantly alters fresh cementitious properties, primarily because of its high specific surface area and layered particle structure

(Muzenda et al., 2020), which contributes to flocculation and high-water demand (Zunino et al., 2020). Consequently, CC is the main factor leading to an increase in static and dynamic yield stress, plastic viscosity, cohesion, and thixotropic index (Hou et al., 2021; Muzenda et al., 2020). This increase in flow resistance presents challenges for workability and material handling. To mitigate this issue, mix designs commonly include limestone powder (Ibrahim et al., 2023). Comparative analyses confirm that although CC systems increase viscosity and yield stress, limestone has an opposite, dampening effect (Hou et al., 2021; Muzenda et al., 2020). Limestone reduces flow resistance by acting as a beneficial filler material and because of its particle characteristics (e.g., a somewhat round or circular shape), which creates a "bearing effect" that enhances flowability (Muzenda et al., 2020; Nguyen et al., 2018). Despite the counteracting effect of limestone, achieving sufficient workability for necessary pumpability, consolidation, and placement requires the strategic use of HRWRs. The increased specific surface area of the CC fraction increases the water demand of LC3, often necessitating 25% to 50% higher dosages of polycarboxylate ether-based HRWRs compared with OPC systems (Zunino et al., 2020). Therefore, superplasticizer dosage must be precisely optimized to compensate for the higher water demand and complex particle interactions (Ferreiro et al., 2017).

Several states have explored the use of CC in their concrete mixtures. Zayed et al. (2018) conducted a comprehensive Florida DOT study to evaluate the feasibility of developing locally available CCs as SCMs to replace Class F FA in Florida concrete mixtures, given the anticipated decline in FA availability. The study systematically characterized 20 native clay deposits across the state in terms of sand content, chemical oxide composition, mineralogy, and calcination behavior. Once separated from substantial sand fractions, the clay-rich portion consistently satisfied ASTM C618 Class N chemical criteria and contained high kaolinite contents (70–90%), enabling strong pozzolanic potential on thermal activation (ASTM International, 2023a). Detailed thermal analyses confirmed full dehydroxylation at 600°C without added benefit from higher calcination temperatures, and mortar testing demonstrated that a 10% cement replacement with CC produced strength indices meeting ASTM requirements at both 7 and 28 days. The findings indicate that Florida's clay resources can be effectively transformed into viable pozzolanic materials for structural concrete applications, supporting further Florida DOT development toward durability evaluations and field implementation.

Nassiri et al. (2023) conducted a comprehensive Caltrans-sponsored assessment to identify alternative SCMs suitable for reducing cement usage and greenhouse gas emissions in California concrete, with a particular emphasis on natural pozzolans such as sedimentary clays. The study evaluated the availability of clay resources in the western United States, their mineralogical characteristics, and the thermal activation requirements needed to enhance pozzolanic reactivity. The literature review synthesized in the report shows that CCs can improve long-term strength and chloride resistance in blended cement systems, although higher water demand and slower early-age strength gain remain concerns. Environmental analyses further indicate that calcination introduces non-negligible processing emissions but still enables significant overall embodied-carbon reductions when replacing clinker at moderate dosages. The study concludes that CCs represent one of the most promising near-term alternatives to declining FA supplies for California's paving sector.

Noorvand et al. (2024) carried out a comprehensive U.S. DOT-sponsored investigation examining locally sourced CCs from across U.S. DOT Region 6 as cost-effective SCM alternatives to address the anticipated decline in FA use. The study included physical, chemical, and mineralogical characterization of five clay sources, demonstrating that three kaolinite-rich materials (> 75–90% kaolinite) exhibited strong pozzolanic reactivity following thermal activation. The objective was to evaluate these CCs both as partial cement replacements and as binders for geopolymer production, aiming to reduce clinker demand in transportation infrastructure concrete. CCs achieved ASTM C618 minimum strength activity indices (ASTM International, 2023a), and concrete mixtures incorporating the CCs showed improved durability through low to very low chloride ion penetration at optimized replacement levels of 20 to 30%. In addition, geopolymer systems synthesized from these clays delivered promising compressive strength, with calcination temperature exerting a greater influence on performance than calcination duration. The authors concluded that these regional clay resources can be effectively activated into SCMs or geopolymer precursors.

Chorzepa et al. (2017) carried out a Georgia DOT investigation aimed at evaluating metakaolin, a thermally activated, kaolinite-rich CC, as a locally available SCM alternative to address diminishing FA and slag supplies in the state. The objective of this study was to determine performance limits for metakaolin in Georgia DOT concrete classes by evaluating strength, durability, shrinkage, thermal expansion, and heat of hydration across binary and ternary replacement systems. Results showed that adding metakaolin significantly improved mechanical properties, reduced chloride penetration, and mitigated both sulfate-induced and alkali–silica reactivity expansion. The study identified an optimal replacement range of 10 to 15% metakaolin for achieving balanced fresh and hardened performance, whereas ternary blends combining 15% metakaolin and 30% slag were recommended for mass concrete applications because of substantial reductions in heat generation.

CCs, particularly when incorporated into LC3 systems, are identified as extremely promising materials for the mitigation of ASR (Scrivener et al., 2019; Zunino et al., 2020). Previous studies have demonstrated that substituting a portion of Portland cement with these clays can reduce ASR-induced expansion to “completely uncritical” levels, even when utilizing highly reactive aggregates (Li et al., 2015; Sabir et al., 2001; Sharma et al., 2021; Zunino et al., 2020). Although high-purity metakaolin is effective at replacement levels of approximately 10 to 15%, lower grade or impure clays have also proven capable of suppressing expansion below standard innocuous limits (Li et al., 2015; Scrivener et al., 2019; Trümer and Ludwing, 2015). This mitigation potential is further enhanced as the clinker substitution level increases, with LC3-50 formulations frequently exhibiting negligible expansion compared with reference Portland cements, when highly reactive aggregates are used (Scrivener et al., 2019).

The primary mechanisms for this mitigation include a significant reduction in pore solution alkalinity and the concentrations of hydroxyl, sodium, and potassium ions (Favier and Scrivener, 2017; Li et al., 2015; Zunino et al., 2020). A critical factor is the release of reactive alumina from the CC into the pore solution, which acts to directly inhibit the dissolution of reactive silicate minerals within the aggregate (Zunino et al., 2020). Furthermore, the pozzolanic reaction drives pore structure refinement, thereby inhibiting the transport of ions necessary for the reaction to progress (Favier et al., 2015; Favier and Scrivener, 2017). The resulting secondary hydration products (calcium alumino silicate hydrates) often feature lower calcium-to-silica ratios, which facilitate the binding of alkali ions and prevent their participation in the formation of expansive ASR gel (Favier et al., 2015).

Life-Cycle Assessment of Concrete Materials

LCA is a standardized methodology used to quantify the environmental impacts of a product, process, or system across all relevant life-cycle stages: from raw material extraction through manufacturing, transportation, use, and end-of-life management (Santos et al., 2021). During recent decades, LCA has become a central tool for evaluating the effectiveness of emerging “low-carbon” concrete technologies. However, considerable variability exists in the way LCAs have been conducted in this domain, leading to challenges when comparing results across studies.

Much of this variability stems from differences in functional units (FU) and system boundaries, which are fundamental LCA framing decisions defined by ISO 14040. The FU is described as “the quantified performance of a product system for use as a reference unit” (ISO, 2006), essentially the basis for normalizing environmental impacts (e.g., per cubic yard of concrete). System boundaries specify which life-cycle stages and processes are included in the evaluation, determining whether the effects associated with use-phase performance or disposal are considered.

Figure 5 provides an overview of LCA approaches used in previously published studies on low-carbon concrete, identified through a structured Google Scholar search using the terms “sustainable concrete” and “life-cycle assessment.” These studies can be broadly grouped into three categories based on how they account for concrete performance in the LCA:

1. **Traditional LCA Framing:** About one-third of the studies (25 of 71) used a volume-based FU and did not incorporate changes in mechanical performance or durability resulting from material modifications.
2. **Mechanical Performance-Adjusted LCA Framing:** Roughly one-half of the studies (36 of 71) incorporated changes in strength or other mechanical properties. Common approaches included normalizing results by strength (e.g., per psi) or comparing mixtures designed to achieve similar performance targets.
3. **Model-Based Performance Estimation:** A smaller subset employed mechanical property prediction models when experimental data were unavailable, then evaluated environmental impacts based on the estimated mix performance.

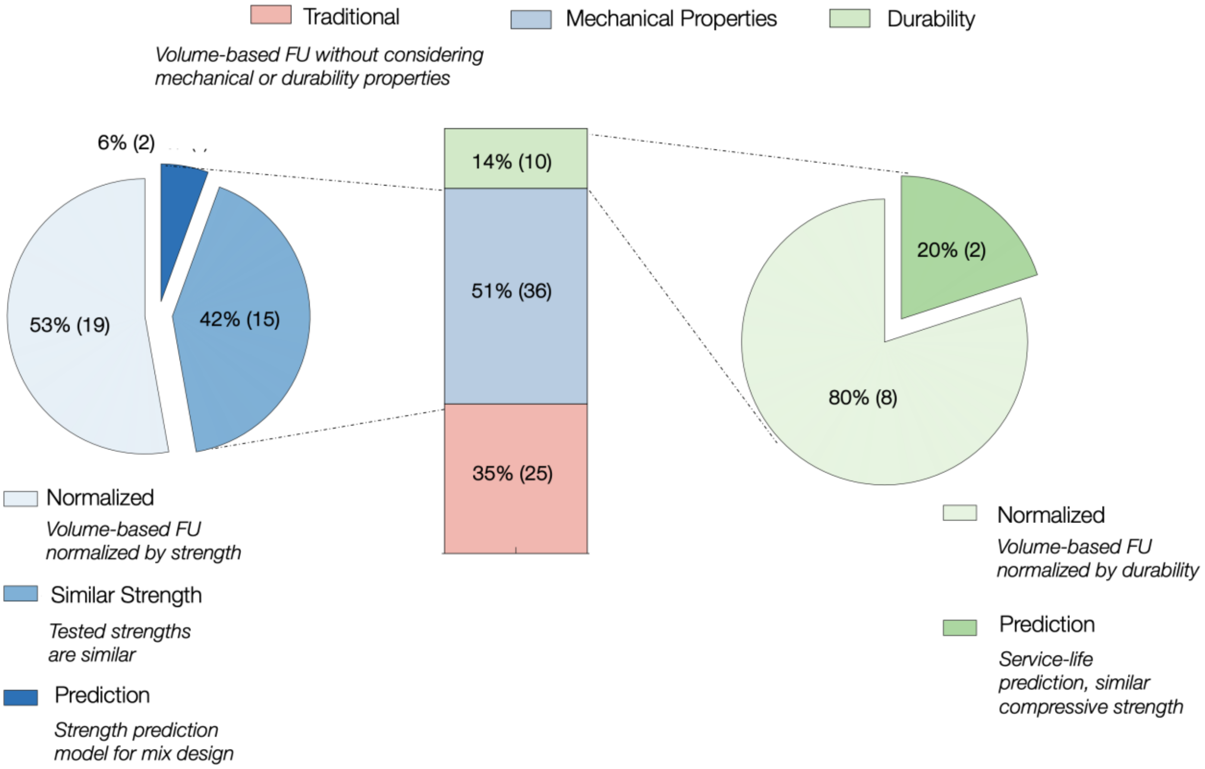


Figure 5. Visual Summary of Life-Cycle Assessment Framing for Sustainable Concrete in 71 Studies Between 2019 and 2023. FU = functional unit.

Studies categorized under the “traditional” and “mechanical” LCA framings primarily focused on the effects associated with raw material extraction and production, which are the stages most directly influenced by changes in binder composition. However, because concrete structures typically exhibit long service lives, it is also important to consider the use phase and end-of-life behavior when evaluating low-carbon technologies. Therefore, the third grouping of studies corresponds to “durability-based” LCA framings, in which the focus is on how improved durability from an innovative mixture could extend the service life of a structure and thereby alter its overall environmental profile. This category included 10 studies that used two main strategies: (1) Durability-normalized FU—two studies quantified environmental impacts per unit of service life—and (2) service life modeling—eight studies estimated durability improvements and evaluated their effect on life-cycle performance.

These durability-focused investigations used cradle-to-grave system boundaries, encompassing all life-cycle stages, including operation and end-of-life processing. By contrast, most other studies limited the analysis to cradle to gate, considering only the effects up to the point of material production. Overall, Figure 5 demonstrates the substantial variability in LCA methodologies applied to low-carbon concrete research, despite the growing need for consistent and reliable metrics such as GWP to support the evaluation and implementation of emerging cementitious technologies.

Characterization of Cementitious Materials

X-Ray Fluorescence Results

Table 4 presents the chemical compositions of the PLC, CC, RCA, and SC used in this study. Notably, CC-2 exhibits a higher calcium oxide (CaO) content compared with CC-1, which is likely attributable to calcite impurities present in the raw clay source. During the calcination process, these calcite impurities can partially decarbonate, resulting in the generation of free lime (CaO).

Table 4. Oxide Chemical Composition of PLC, CC, Fly Ash, and SC

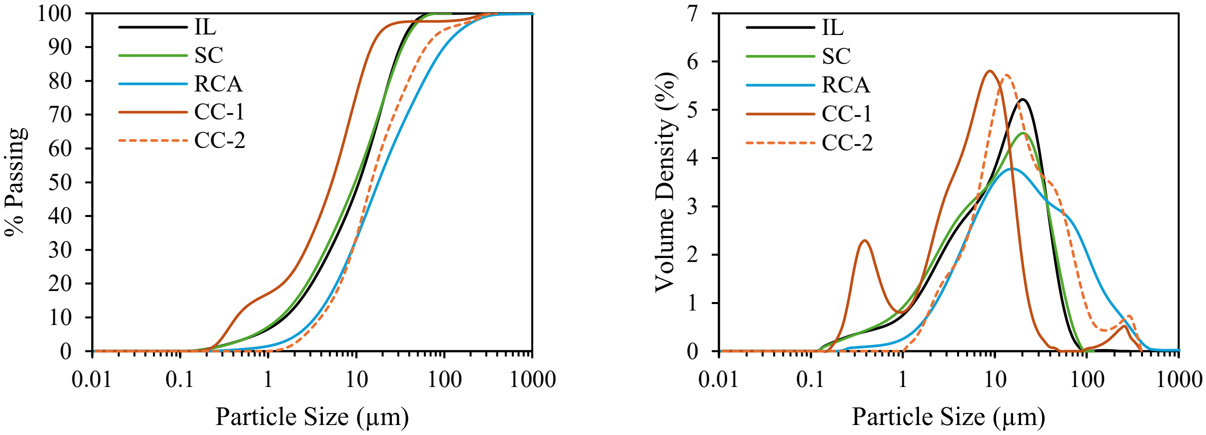
	PLC	CC		RCA	SC
		CC-1	CC-2		
SiO_2	16.81	47.33	53.58	53.94	32.97
Al_2O_3	3.79	46.67	33.22	30.08	9.23
Fe_2O_3	3.27	1.88	2.51	7.84	0.64
CaO	68.01	0.33	6.40	1.08	44.60
Na_2O	0.07	0.06	0.04	0.29	0.10
K_2O	0.79	0.12	1.52	3.43	0.44
SO_3	3.61	0.06	0.31	0.07	2.63
SiO_2+Fe_2O_3+Al_2O (%)	23.87	95.88	89.31	91.86	42.84
Total Alkali (%Na_2O_{eq})	0.59	0.14	1.04	2.55	0.39
Loss on Ignition (%)	1.00	0.96	3.15	0.46	0.34

CC = calcined clay; PLC = Portland limestone cement; RCA = reclaimed coal ash (Class F); SC = slag cement.

In accordance with the chemical requirements for Class N pozzolans specified in ASTM C618 (ASTM International, 2023a), the combined content of silicon dioxide (SiO_2), iron oxide (Fe_2O_3), and aluminum oxide (Al_2O_3), must total at least 70%, with a maximum sulfur trioxide (SO_3) content of 4%, and a maximum loss on ignition of 10%. Accordingly, both CCs employed in this study satisfied the chemical requirements for Class N pozzolans evaluated.

Particle Size Analysis

Figure 6 presents the particle size distribution curves of all the cementitious materials used in this study obtained by laser diffraction analysis. As the cumulative distribution plot shows, CC-1 exhibits significantly finer particles, with the 10th percentile particle size (D10), median particle size (D50), and 90th percentile particle size (D90) of 0.4 µm, 5.3 µm, and 15.3 µm, respectively, compared with 4 µm, 15 µm, and 60.4 µm for CC-2. The mean particle size of CC-1 (11.3 µm) is also substantially less than that of CC-2 (30 µm), further highlighting its greater fineness. It is also noted that Type IL cement and SC exhibit similar particle size distributions, falling between those of CC-1 and CC-2. Furthermore, RCA shows the coarsest particle size distribution among the materials evaluated, although it remains close to that of CC-2.

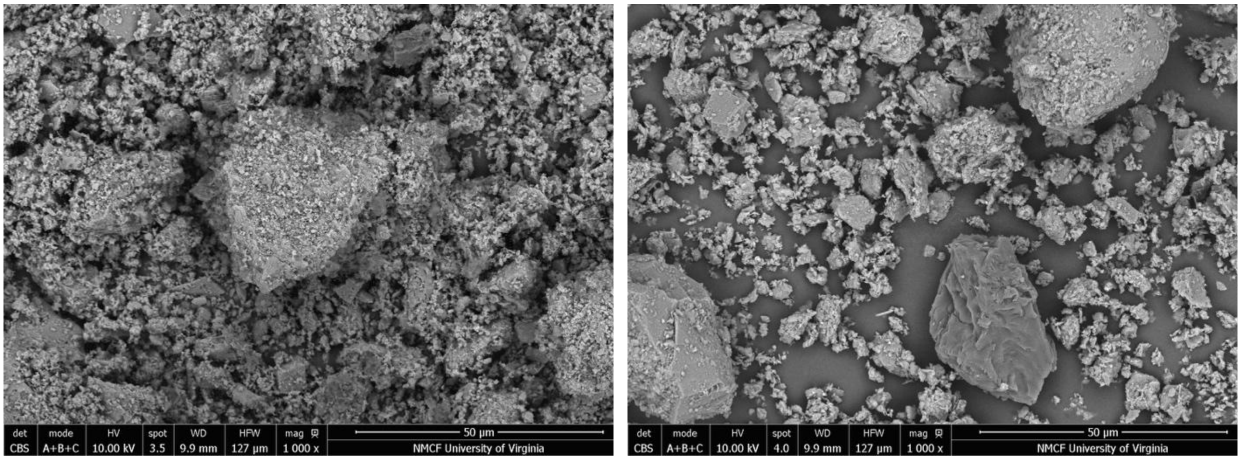


(a) (b)

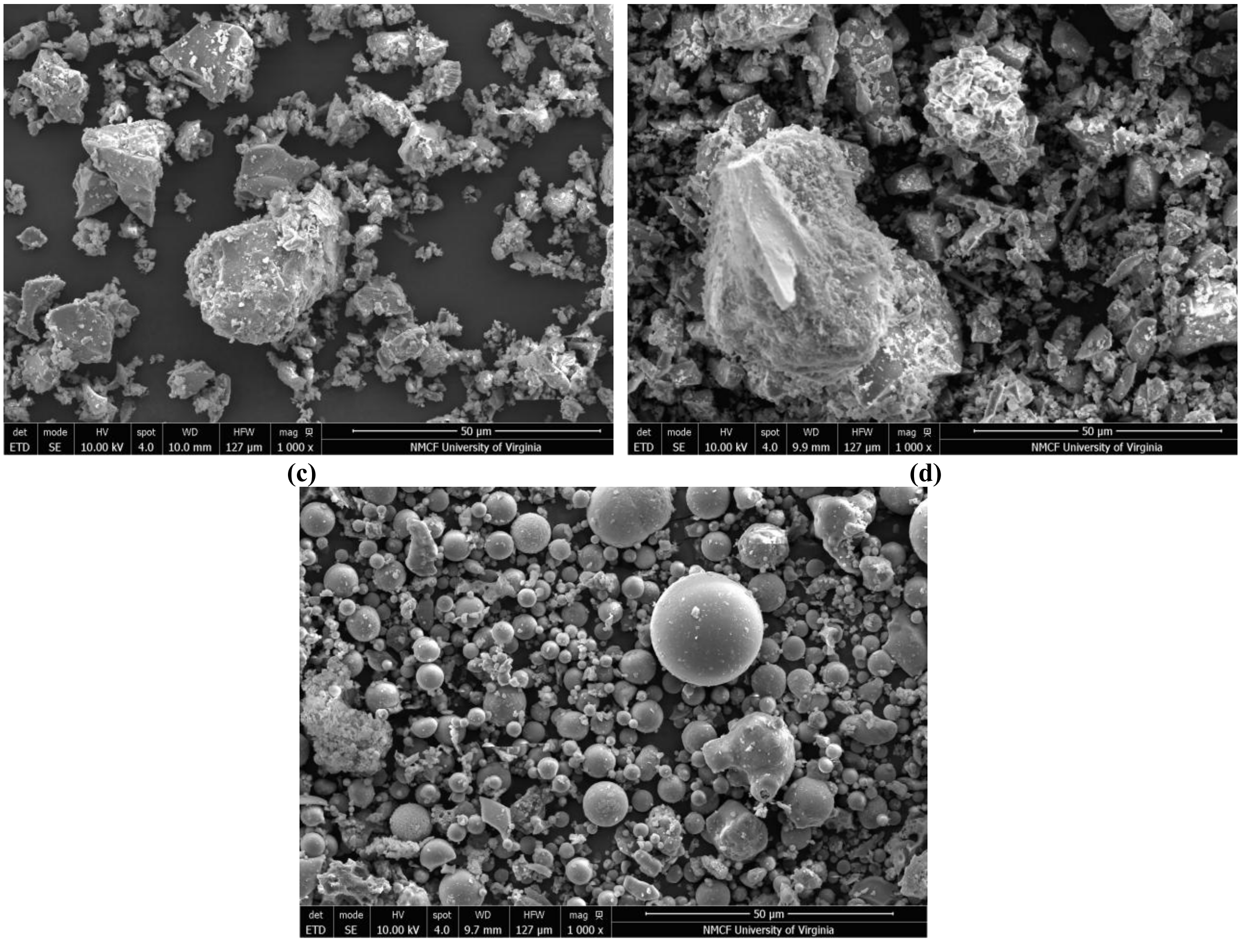
Figure 6. Particle Size Distribution of Cementitious Materials Evaluated: (a) Cumulative % Passing Curves; (b) Volume Density Distributions. CC = calcined clay; IL= type IL cement; RCA = reclaimed coal ash (Class F); SC = slag cement.

Scanning Electron Microscopy Results

The micromorphology of CC-1 and CC-2 exhibited differences (Figure 7). CC-1 consisted of highly fine, agglomerated, plate-like particles forming a porous structure with a high surface area. In contrast, CC-2 displayed coarser particles with lower porosity and surface area, although small plate-like features were also present. The relatively sintered appearance of CC-2 could result from higher calcination temperature or prolonged exposure, causing partial melting and particle fusion (Fernandez et al., 2011). In the case of Type IL cement and SC, a similar morphology is observed, characterized by predominantly irregular and angular particles. Furthermore, RCA exhibits the typical sphere-like morphology associated with conventional FA.



(a) (b)



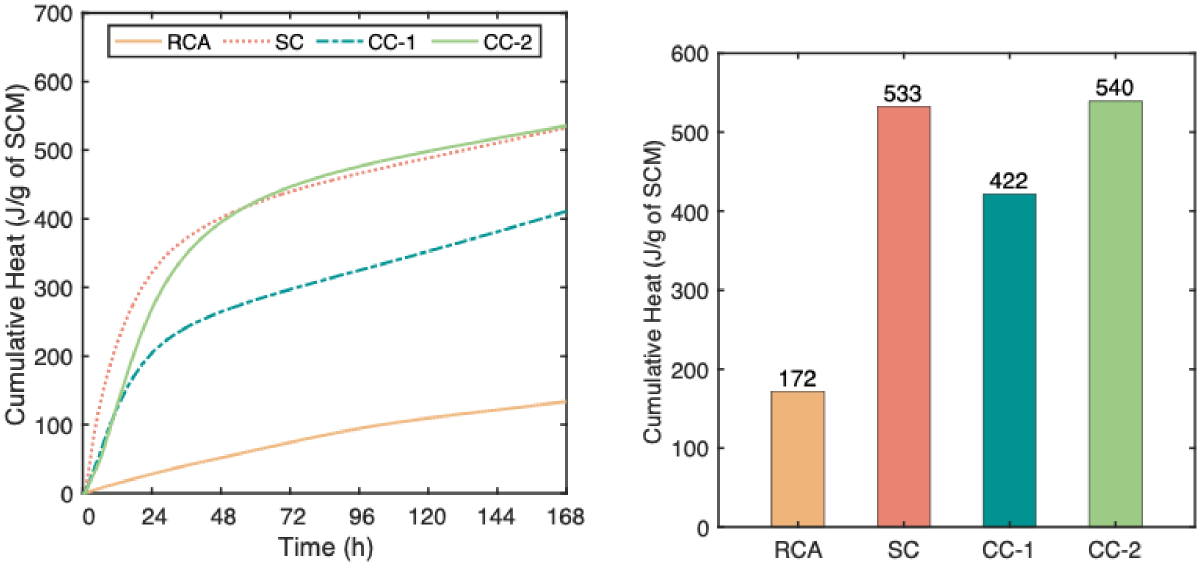
(c) **(d)**

(e)

Figure 7. Scanning Electron Microscopy Images Showing Morphology of Cementitious Materials Evaluated: (a) CC-1; (b) CC-2; (c) Type IL Cement; (d) Slag Cement; (e) Reclaimed Coal Ash (Class F). CC = calcined clay.

Rapid, Relevant, and Reliable Reactivity Test Results

Figure 8a presents the cumulative heat of hydration curves for the SCMs evaluated, and Figure 8b shows the 7-day cumulative heat values. At early ages, CC-1 and CC-2 exhibit comparable cumulative heat, both showing a sharp initial increase. As time progresses, however, their reaction rates diverge: CC-2 maintains a relatively higher rate, whereas CC-1 displays a more pronounced deceleration. Over time, the reaction rates for both clays converge, although their early divergence results in differing cumulative heat values at 7 days. In this study, the manufacturer ground CC-1 to achieve a finer particle size, whereas the authors ground and subsequently sieved CC-2. Despite being relatively coarser, CC-2 demonstrated higher reactivity than CC-1, likely because of its significantly higher CaO content (Table 4), which can provide partial hydraulic characteristics in addition to its pozzolanic behavior.



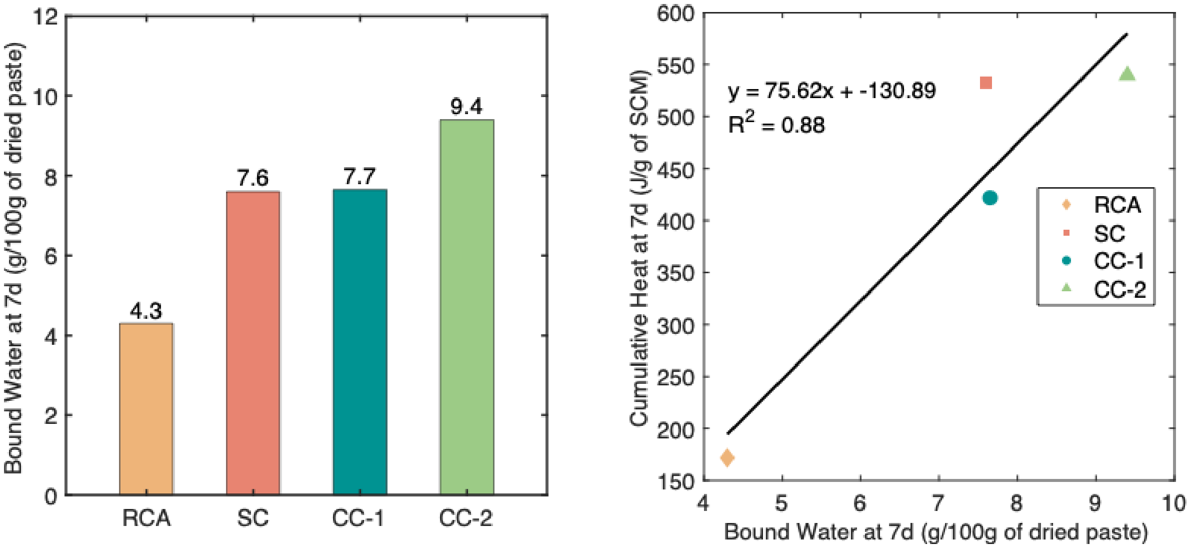
(a) **(b)**

Figure 8. Cumulative Heat of Hydration of SCMs: (a) Cumulative Heat Evolution During 7 Days; (b) Cumulative Heat Values at 7 Days. CC = calcined clay; RCA = reclaimed coal ash (Class F); SC = slag cement; SCMs = supplementary cementitious materials.

Compared with RCA, which exhibited the lowest cumulative heat throughout the test period, both CCs demonstrated much higher reactivity. The gradual increase in cumulative heat for RCA suggests a slower but continuous reaction process. This low early reactivity can be attributed to its low CaO content, predominance of unreacted crystalline phases, and limited specific surface area compared with the other SCMs (Schnürer et al., 2026; Shearer et al., 2024). Consequently, the delayed heat release of RCA implies that its pozzolanic contribution is expected mainly at later ages (Ramanathan et al., 2022).

Relative to SC, CCs presented a similar reactivity, particularly CC-2. However, SC showed a more rapid heat release during the first 24 hours, suggesting high early-age reactivity. This behavior is primarily attributed to its amorphous structure and elevated CaO content, which enhances hydraulic activity. The amorphous slag structure of SC dissolves readily, accelerating hydration and contributing to a higher early heat evolution rate (Zhang et al., 2022).

Figure 9a presents the bound water content of pastes incorporating the different SCMs at 7 days. The amount of chemically bound water reflects the extent of hydration products formation, hence serving as an indicator of reactivity. Accordingly, the bound water results generally follow the same trend as the cumulative heat data, with minor differences in relative magnitudes. As Figure 9b shows, a strong linear relationship ($R^2 = 0.88$) was observed between cumulative heat and bound water, confirming that heat evolution and chemically bound water are closely correlated measures of SCM reactivity.



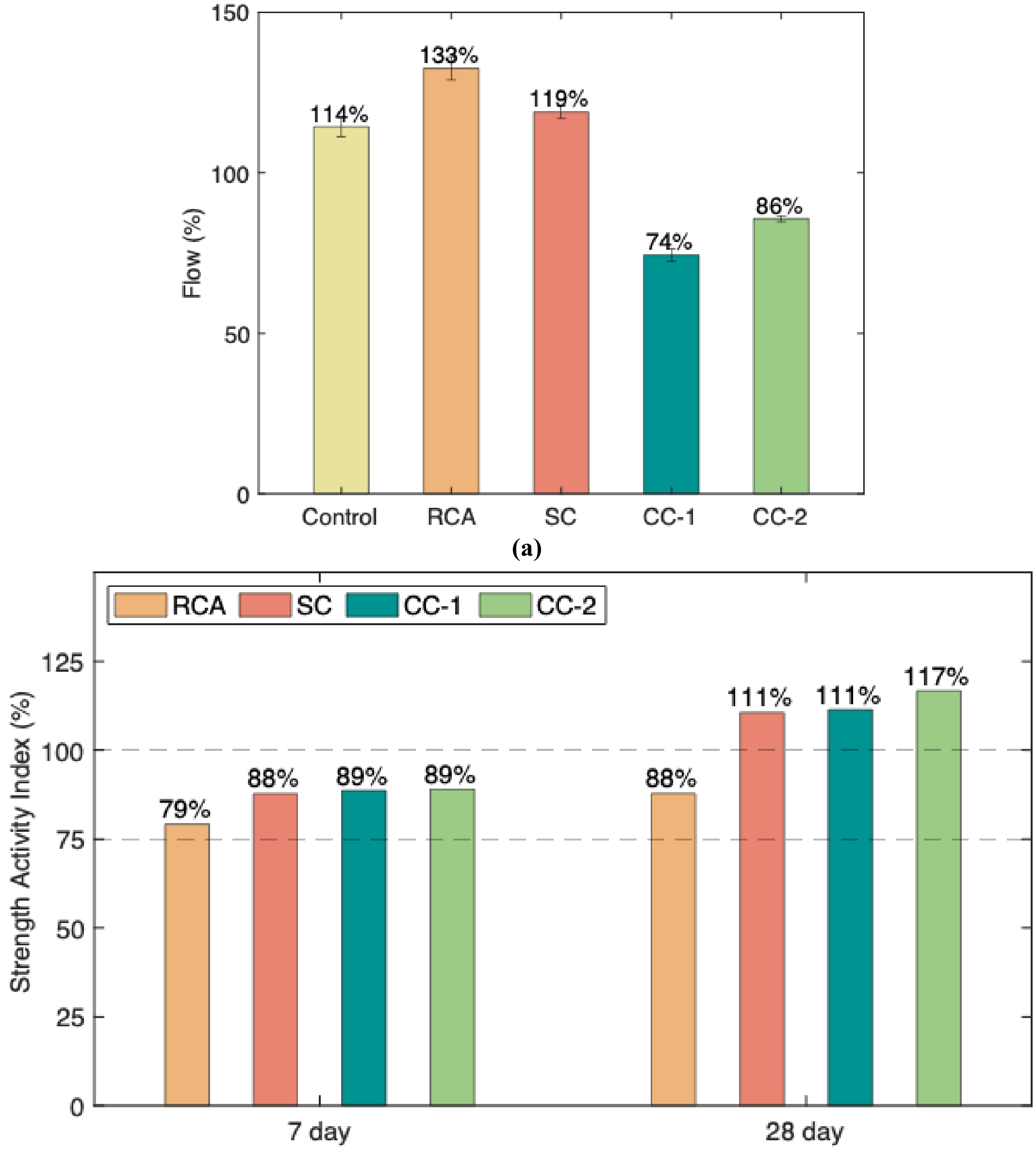
(a) **(b)**

Figure 9. (a) Bound Water Content of Pastes Incorporating Different SCMs; (b) Correlation Between Cumulative Heat and Bound Water. CC = calcined clay; RCA = reclaimed coal ash (Class F); SC = slag cement; SCMs = supplementary cementitious materials.

Strength Activity Index

Figure 10 presents the flow and SAI values of the SCMs. Incorporating CC-1 and CC-2 significantly reduced flow by 25 to 35% relative to the control. This reduction is consistent with their porous morphology observed in the scanning electron microscopy images and their higher specific surface area, both of which increase water demand. Among the two clays, CC-1, which has a finer particle size than CC-2, exhibited the lowest flow. The smaller particle size of CC-1 results in a larger surface area available for water adsorption, thereby increasing the mix's water demand and reducing flowability (Benkeser et al., 2022). On the other hand, RCA increased the flow relative to control by approximately 16%, whereas SC presented a similar flow to control. The enhanced workability achieved with RCA is mainly attributed to the spherical shape of its particles, which reduces internal friction and facilitates better packing and lubrication among cement grains.

The SAI values for the two CCs were 89% at 7 days and 111% and 117% at 28 days for CC-1 and CC-2, respectively. In turn, both CCs met the ASTM C618 minimum SAI requirement for Class N pozzolans of 75% at 7 or 28 days (ASTM International, 2023a). Compared with CC-2, which had an initial kaolinite content of approximately 30% before calcination, CC-1 contained a significantly higher kaolinite content of around 87%. However, systems containing high calcined metakaolin content (i.e., > 65%) tend to refine their pore structure earlier, which can limit further clinker hydration and slightly reduce long-term strength gain (Avet and Scrivener, 2018; Zunino and Scrivener, 2021). This outcome explains why CC-1 and CC-2 exhibited similar SAI values at both curing ages, despite differences in kaolinite content. Furthermore, CC-2 produced better workability than CC-1, which may have led to a less compact matrix with higher porosity, resulting in marginally lower compressive strength (Benkeser et al., 2022). Importantly, the SAI of both CCs was comparable with that of SC and significantly higher than that of RCA, which is in close agreement with the R3 reactivity test results.

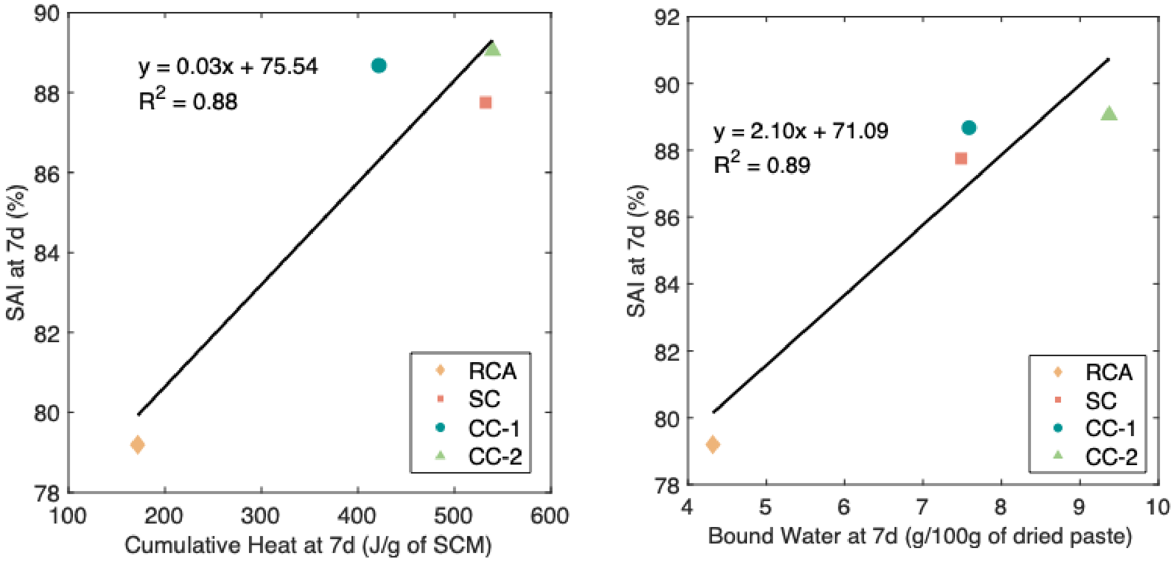


(a)

(b)

Figure 10. (a) Flow Values of Mortar Mixtures Containing Different SCMs; (b) Strength Activity Index of Mortars with SCMs at 7 and 28 Days. CC = calcined clay; RCA = reclaimed coal ash (Class F); SC = slag cement; SCMs = supplementary cementitious materials.

Figure 11 illustrates the correlation between the 7-day SAI of SCM mortars and their corresponding cumulative heat (Figure 11a) and bound water contents (Figure 11b) from the R3 reactivity test results. Strong linear relationships are observed in both cases, with respective R^2 values of 0.88 and 0.89. These results suggest that the SAI determined at a constant w/b, a modified approach from the standardized SAI test, can serve as a reliable and practical indicator of SCM reactivity. This method is straightforward to perform, does not require specialized instrumentation, and effectively captures the relative reactivity trends among different SCMs.



(a) **(b)**

Figure 11. Correlation Between SAI and (a) Cumulative Heat; (b) Bound Water at 7 Days. CC = calcined clay; d = days; RCA = reclaimed coal ash (Class F); SAI = strength activity index; SC = slag cement; SCM = supplementary cementitious material.

Evaluation of the Properties of Concrete Incorporating LC2 and LC3 Systems

Fresh Properties

Figure 12 displays the slump measurements and visual consistency of the fresh concrete mixtures, and Table 5 summarizes the fresh properties of the concrete mixtures. All mixtures achieved slump values within the target range of 2 to 4 inches, indicating that the use of water-reducing admixtures effectively maintained consistent workability across different binder systems. As expected, mixtures incorporating CC (IL-30CC, LC3, and IL-50CC) required noticeably higher HRWR dosages to achieve the desired slump because of the higher surface area and greater water demand of metakaolin-rich particles. To achieve similar workability to control, IL-30CC and LC3 required approximately 6 times more HRWR, whereas IL-50CC required nearly 14 times more HRWR.

Air contents for all mixtures remained within or very close to the specified tolerance of 6.5% ± 1.5%, indicating acceptable control of air entrainment despite the different binder compositions. However, the IL-30RCA required nearly double the amount of AEA to achieve the desired air content. This observation aligns with prior observations that coal ashes can reduce air void stability and increase the demand for AEAs. Importantly, the use of CC did not produce any significant effect on the demand of AEA. This outcome is an important observation because controlling adequate air content in concrete can be a practical challenge when using coal ashes, which can lead to the rejection of concrete loads.

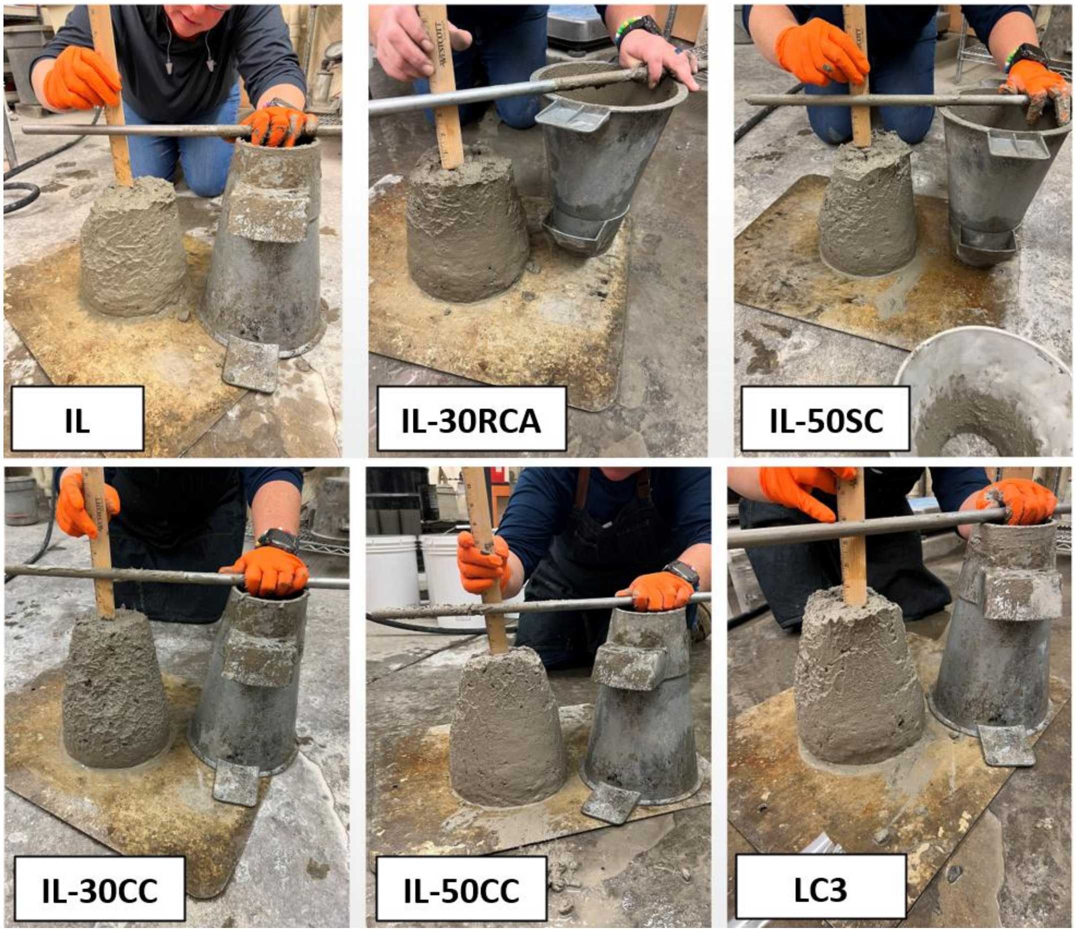


Figure 12. Slump Test Observations for Concrete Mixtures with Different Binder Systems

Table 5. Summary of Fresh Properties

Mix ID	Unit Weight, lb/ft^3 (ASTM C138)	Air Content, % (ASTM C231)	Slump, inches (ASTM C143)	AEA[a]	WR[a]	HRWR[a]
IL	146.2	5.5	3.5	0.45	2.28	0.58
IL-30RCA	145.9	4.8	3.4	0.82	0.19	0.00
IL-50SC	147.5	4.9	2.6	0.45	2.28	0.20
IL-30CC	145.8	5.8	2.9	0.45	2.28	3.40
LC3	144.5	5.8	2.8	0.45	2.28	3.28
IL-50CC	145.1	5.9	2.8	0.45	2.28	8.18

AEA = air-entraining admixture; CC = calcined clay; HRWR = high-range water reducer; IL = type IL cement; LC3 = limestone calcined clay cement; RCA = reclaimed coal ash (Class F); SC = slag cement; WR = water reducer. [a] Dosage in fluid ounce per 100 pounds of cementitious materials.

Compressive Strength

Figure 13 presents the compressive strength development of concrete mixtures incorporating different binders, tested at 7, 28, 90, and 196 days. All concrete mixtures exhibited progressive strength gains over time, reflecting the continued hydration of cement and the pozzolanic reactions of SCMs.

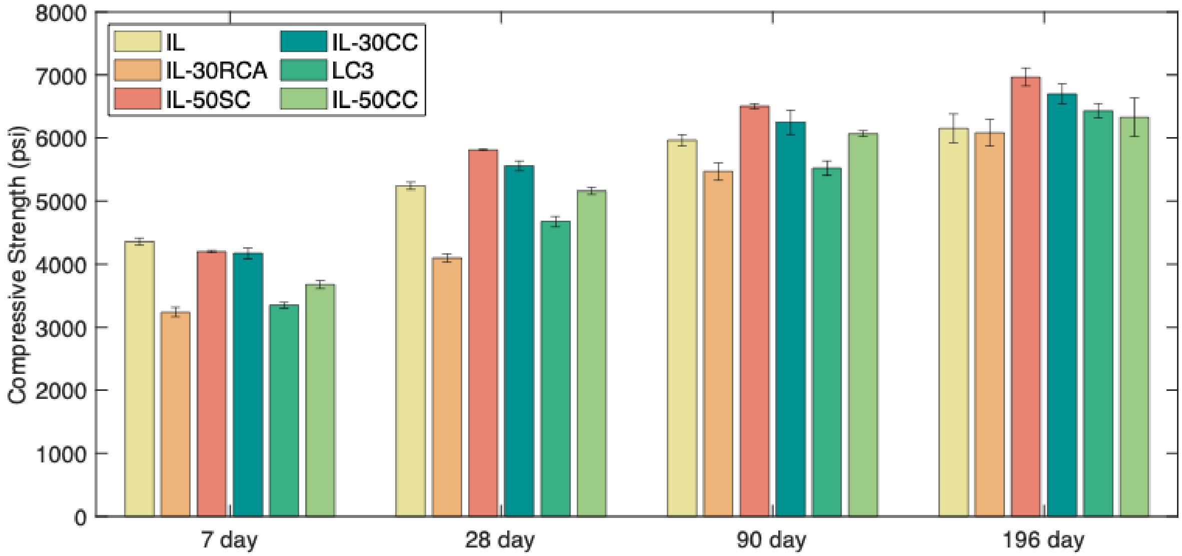


Figure 13. Compressive Strength Development of Concrete Mixtures Incorporating Different Supplementary Cementitious Materials at 7, 28, 90, and 196 Days. CC = calcined clay; IL = type IL cement; LC3 = limestone calcined clay cement; RCA = reclaimed coal ash (Class F); SC = slag cement.

At 7 days, the IL mixture exhibited the highest compressive strength, whereas mixtures incorporating SCMs showed lower values, mainly because of the dilution effect and the delayed onset of pozzolanic reactions. Among the SCM systems, IL-30CC and IL-50SC demonstrated relatively higher early-age strengths than the other three mixtures, showing only about a 4% reduction compared with the IL mixture. In contrast, the IL-30RCA mixture exhibited the greatest reduction, with a 26% lower strength at 7 days. At 7 days, the LC3 exhibited a 23% and 20% reduction in strength relative to the control and the IL-30CC, respectively. By 28 days, the strength differences among the mixtures became less pronounced, with IL-30CC and IL-50SC surpassing the IL mixture by approximately 11% and 6%, respectively. This improvement can be attributed to the formation of additional calcium silicate hydrate phases from the latent hydraulic reaction of slag and calcium alumino silicate hydrate phases from the pozzolanic reaction of CC. The IL-30CC and IL-50SC mixtures maintained this relative advantage over the IL mixture at both 90 and 196 days. Meanwhile, the LC3 and IL-50CC systems continued to exhibit steady strength gains beyond 90 days, achieving slightly higher values than the IL mixture at 196 days, reflecting their sustained long-term reactivity. The IL-30RCA mixture consistently showed the lowest strength across all curing ages but reached a strength comparable with that of the IL mixture by 196 days, indicating its delayed but continuous pozzolanic activity.

Elastic Modulus

Table 6 shows the measured elastic modulus and Poisson's ratio values of all concrete mixtures at 28, 90, and 196 days of curing. The elastic modulus results indicate that all mixtures exhibited a consistent increase in stiffness, reflecting continued hydration and microstructural densification up to 196 days. At 28 days, the IL mixture showed an elastic modulus of 3.66×10^6 psi, whereas mixtures containing SCMs produced slightly lower modulus, ranging from 3.38 to 3.58×10^6 psi. By 196 days, IL-30CC, IL-30RCA, and IL-50SC exceeded the modulus of the IL mixture, with IL-30CC achieving the highest value of 4.75×10^6 psi, indicating enhanced long-term matrix refinement for mixtures with SCMs. The LC3 and IL-50CC mixtures also reached modulus values comparable with the control at later ages, confirming that structural stiffness can be maintained even with significant reductions in clinker content.

Table 6. Elastic Modulus and Poisson's Ratio of Concrete Mixtures at 28, 90, and 196 days

Mix ID	Elastic Modulus (psi)			Poisson's Ratio		
	28 Days	90 Days	196 Days	28 Days	90 Days	196 Days
IL	3.66×10^6	4.05×10^6	4.30×10^6	0.16	0.17	0.19
IL-30RCA	3.38×10^6	4.05×10^6	4.60×10^6	0.17	0.18	0.18
IL-50SC	3.58×10^6	4.18×10^6	4.57×10^6	0.17	0.19	0.18
IL-30CC	3.47×10^6	3.98×10^6	4.75×10^6	0.14	0.18	0.19
LC3	3.47×10^6	3.98×10^6	4.31×10^6	0.17	0.18	0.18
IL-50CC	3.50×10^6	3.93×10^6	4.26×10^6	0.16	0.17	0.18

CC = calcined clay; IL = type IL cement; LC3 = limestone calcined clay cement; RCA = reclaimed coal ash (Class F); SC = slag cement.

Chloride Permeability

Figure 14 presents the chloride ion penetrability of the concrete mixtures at 28 and 196 days, evaluated using the rapid chloride permeability test. At both 28 and 196 days, the IL mixture shows a high level of chloride ion permeability (CIP) per ASTM C1202 (ASTM International, 2022b), passing well more than 4,000 Coulombs. Incorporation of SCMs significantly improved chloride resistance in all cases. Mixtures containing 30% CC (IL-30CC and LC3) fell within the low and very low CIP categories at 28 and 196 days, respectively. In contrast, IL-30RCA presented high CIP at 28 days yet catches up at 196 days, falling into the very low CIP category. This result indicates the slower reaction of RCA relative to CC. In the case of IL-50CC and IL-50SC, very low CIP is achieved at 28 days, indicating substantial refinement of pore structure with a higher level of SCM replacement. Importantly, by 196 days, all SCM-containing systems fall into the very low CIP category, reflecting continued hydration and pozzolanic reactions that densify the microstructure over time, leading to durable systems. The reduced permeability aligns well with the previously observed strength gain and calcium hydroxide consumption trends.

Surface Resistivity

Figure 15 presents the surface resistivity development of the concrete mixtures at 7, 28, 90, and 196 days. Overall, SCM incorporation significantly increases electrical resistivity compared with the IL mixture, indicating a more refined and less connected pore network. At 28 days, all SCM-containing mixtures exhibit higher resistivity than the IL cement mixture, with CC (IL-30CC, IL-50CC, and LC3) and slag (IL-50SC) systems already falling into the moderate to low CIP range per AASHTO T358 classifications. Meanwhile, the Type IL mixture remains in the high-penetrability category.

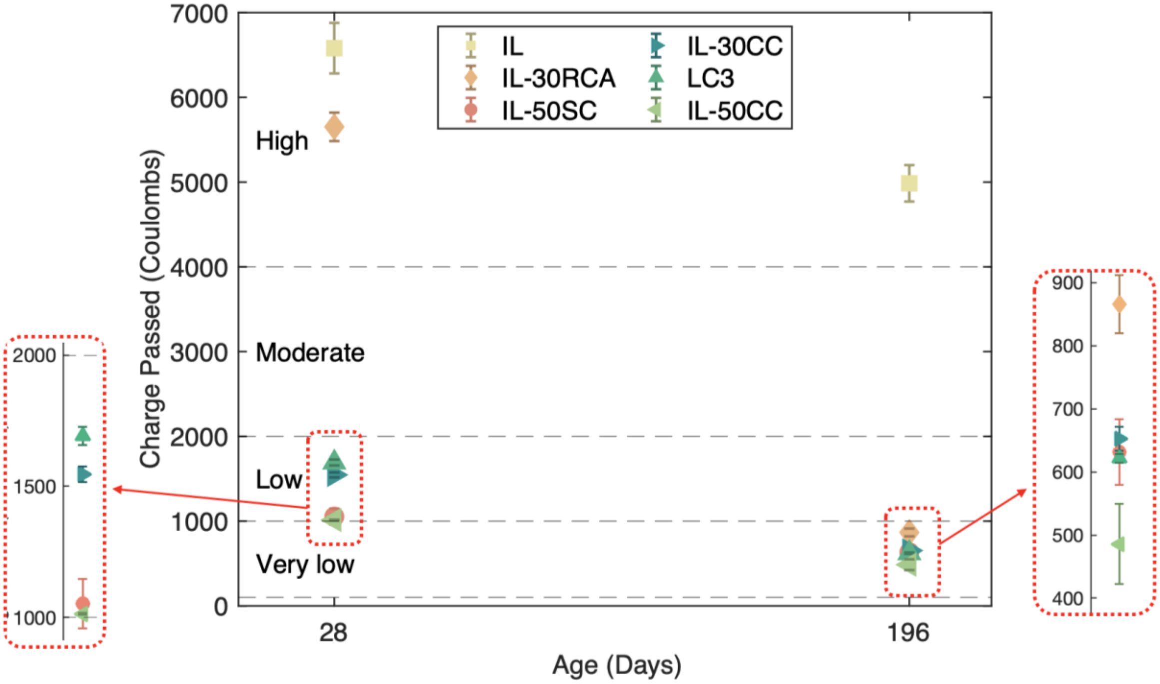


Figure 14. Rapid Chloride Permeability Test Results Showing Charge Passed Through Concrete Specimens at 28 and 196 Days. CC = calcined clay; IL = type IL cement; LC3 = limestone calcined clay cement; RCA = reclaimed coal ash (Class F); SC = slag cement.

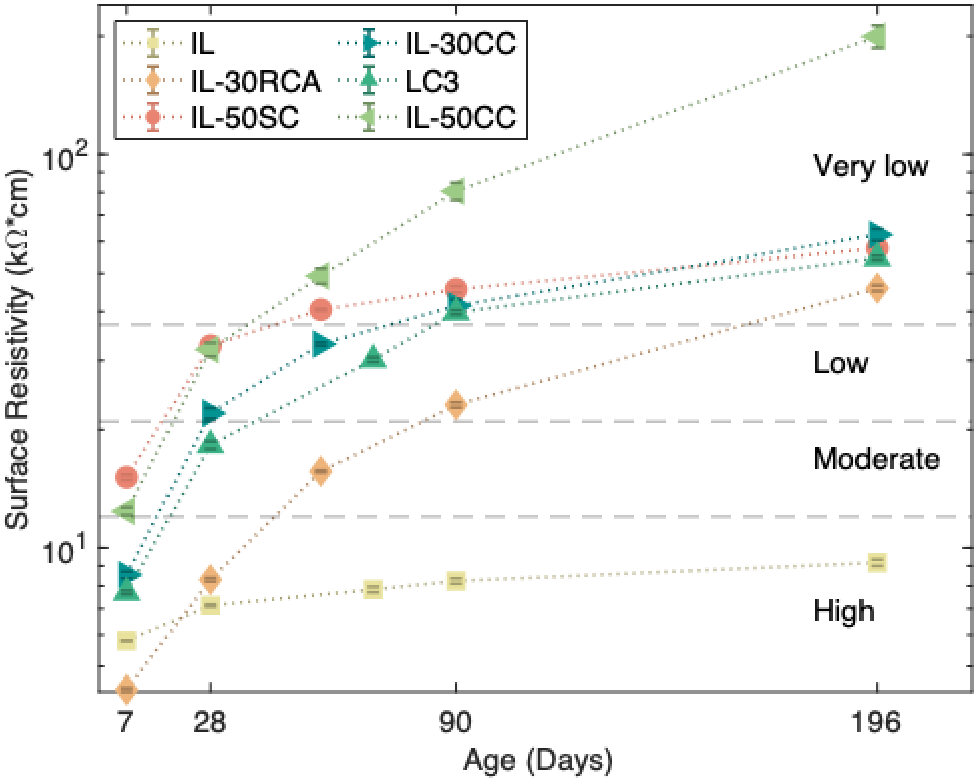


Figure 15. Surface Resistivity Development of Concrete Mixtures at 7, 28, 90, and 196 Days. CC = calcined clay; IL = type IL cement; LC3 = limestone calcined clay cement; RCA = reclaimed coal ash (Class F); SC = slag cement.

At both 90 and 196 days, CC (IL-30CC, IL-50CC, and LC3) and slag (IL-50SC) systems reach the very low CIP classification. In contrast, the control mixture stays in the high CIP category even at 196 days, further confirming the limited pore refinement in PLC-only systems. The IL-30RCA mix improves but remains less resistant to chloride ion penetration than CC- and SC-based systems, reflecting slower pozzolanic kinetics of FA. Nevertheless, the IL-30RCA reaches low CIP at 90 days and very low CIP classification at 196 days. In general, resistivity test results align well with findings from the rapid chloride permeability test.

Sorptivity

Figure 16 shows the initial and secondary water absorption rates (sorptivity) of concrete mixtures incorporating different SCMs after 196 days of curing. The reference mixture (IL) exhibited the highest initial and secondary sorptivity values, indicating a more permeable pore network prone to rapid water transport. In contrast, all SCM-containing systems displayed markedly reduced sorptivity, reflecting their denser microstructures and refined capillary pores.

The mixture with 50% SC (IL-50SC) achieved the lowest absorption rates in both stages, followed closely by IL-30CC and IL-50CC, confirming the strong influence of both SC and CC on reducing porosity and pore connectivity. The LC3 and IL-30CC mixtures performed comparably, suggesting that the synergistic effect of CC and limestone effectively mitigates capillary suction, even at moderate replacement levels. The RCA mixture (IL-30RCA) also showed a noticeable reduction in both initial and secondary sorptivity compared with the control, although its improvement was less pronounced than those achieved with SC or CC, particularly for the initial sorptivity. Overall, these results indicate that SCM incorporation substantially enhances the watertightness and durability of concrete by minimizing moisture ingress and associated deterioration risks. These results align with the electrical-based permeability measurements made using the rapid chloride permeability test and surface resistivity.

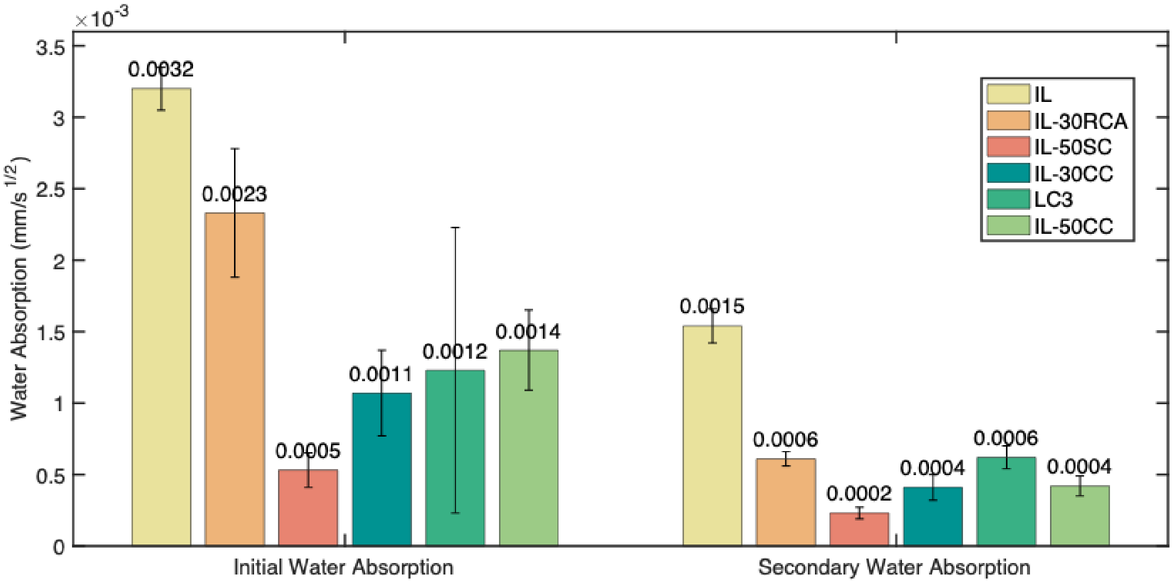


Figure 16. Initial and Secondary Water Absorption Coefficients of Concrete Mixtures Incorporating Different Binder Systems. CC = calcined clay; IL = type IL cement; LC3 = limestone calcined clay cement; RCA = reclaimed coal ash (Class F); SC = slag cement.

Chloride Migration Coefficient

Figure 17 shows the non-steady-state chloride migration coefficients of various cementitious systems. The experimental data reveal a pronounced improvement in chloride transport resistance upon the inclusion of SCMs, demonstrated by a nearly order of magnitude reduction in the non-steady-state migration coefficient, decreasing from a reference value of 20.4 × 10^{-12} m^2/s to values ranging from 1.9 × 10^{-12} m^2/s to 5.6 × 10^{-12} m^2/s. This substantial enhancement in resistance to chloride ingress is consistent with literature findings for CC systems such as LC3, for which the chloride diffusion coefficient is consistently reported to be 5 to 10 times less than that of reference OPC concrete (Dhandapani et al., 2024). In addition, LC3 binders achieve this excellent chloride resistance quickly, showing an improvement of 80 to 90% by 28 days compared with OPC, owing to the high, early reactivity of CCs, which distinguishes them from slower reacting SCMs like FA (Dhandapani et al., 2018).

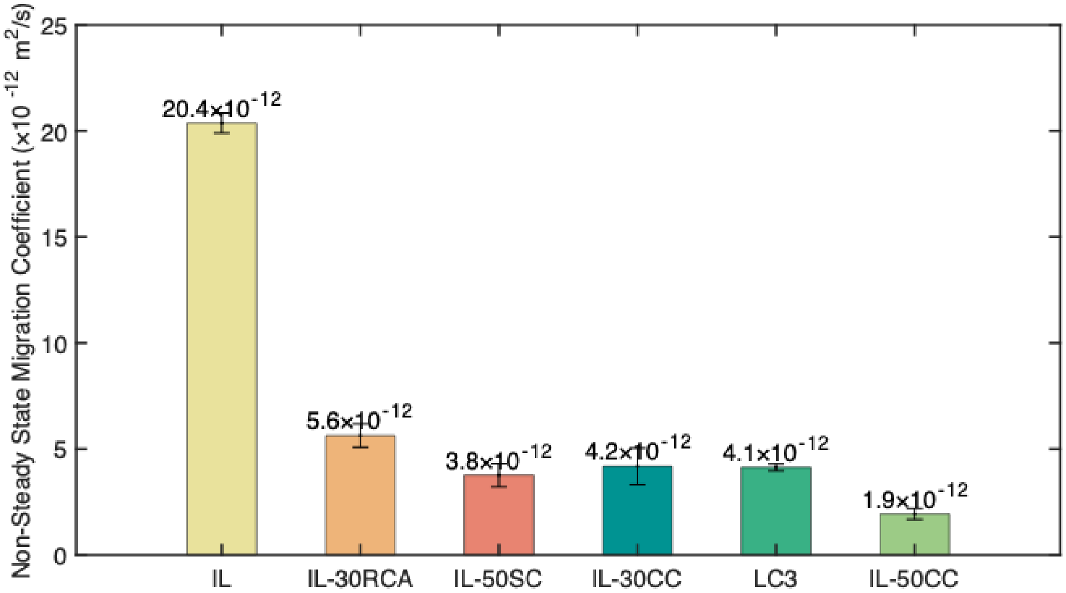


Figure 17. Non-Steady-State Migration Coefficients of Concrete Mixtures Incorporating Different Binder Systems. CC = calcined clay; IL = type IL cement; LC3 = limestone calcined clay cement; RCA = reclaimed coal ash (Class F); SC = slag cement.

The observed reduction in ionic permeability can be attributed to significant microstructural refinement resulting from the SCMs' combined pozzolanic and filler effects. The consumption of calcium hydroxide leads to the formation of secondary hydration products, primarily calcium alumino silicate hydrate and crystalline aluminate phases (Afroz et al., 2023; Dhandapani et al., 2018). The formation of these expansive phases densifies the matrix, reducing the total capillary pore space and, more importantly, severely decreasing the connectivity of the porosity. This mechanism effectively increases the tortuosity of the path chloride ions must travel, which is considered a key factor governing the high resistance of LC3-like systems (Dhandapani et al., 2024). The moderate variability among SCM systems suggests that both material type and replacement level influence ionic transport behavior, likely because of differences in hydration kinetics, secondary calcium alumino silicate hydrate formation, and pore-size distribution. Overall, the results confirm that SCM incorporation markedly improves the microstructural integrity and durability of the concrete, providing an effective means of mitigating chloride-induced deterioration.

Drying Shrinkage

Figure 18 illustrates the drying shrinkage behavior of concrete mixtures up to 127 days. During the moist curing stage (0–7 days), all mixtures exhibited slight expansion, primarily due to ongoing hydration and ettringite formation (Liang et al., 2023; Nguyen et al., 2022). After exposure to drying conditions at 7 days, all concretes experienced shrinkage because of moisture loss and the development of capillary stresses.

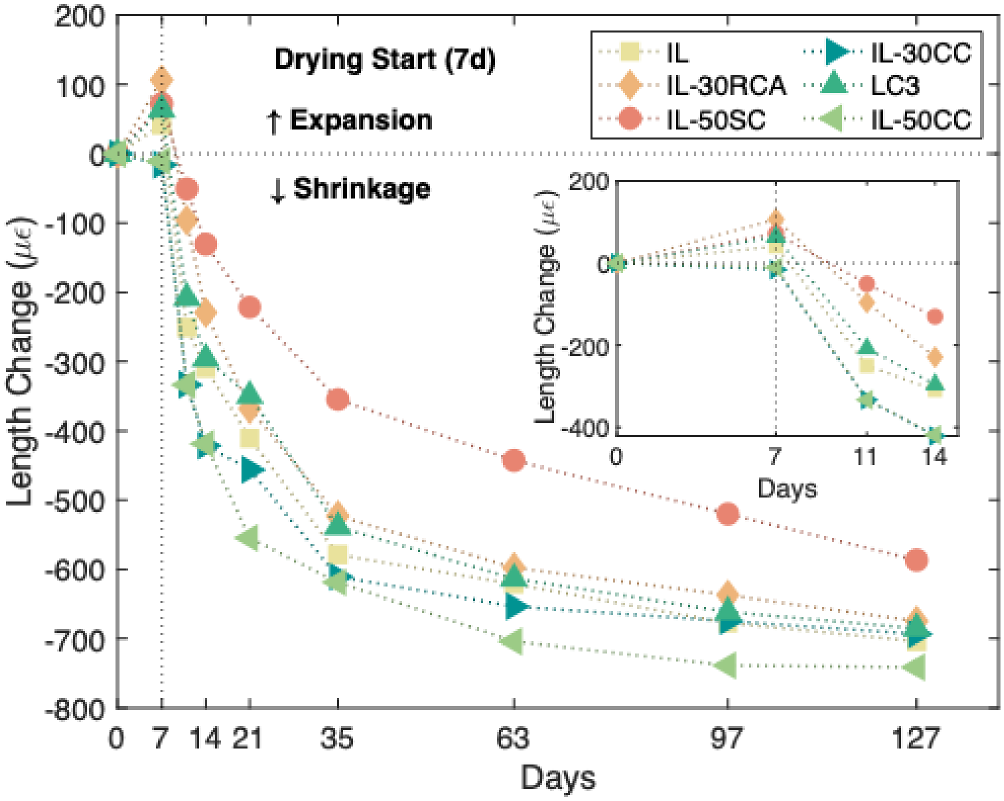


Figure 18. Drying Shrinkage Development of Concrete Mixtures up to 127 Days. CC = calcined clay; IL = type IL cement; LC3 = limestone calcined clay cement; RCA = reclaimed coal ash (Class F); SC = slag cement.

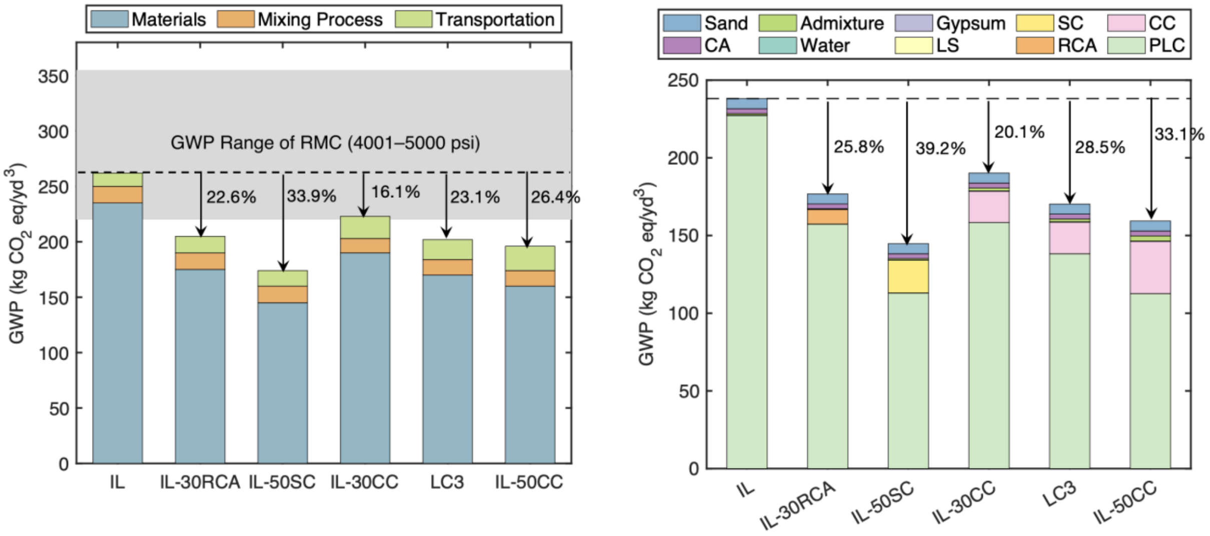
Among the mixtures, IL-50SC demonstrated the lowest drying shrinkage throughout the test period (approximately 500 με at 127 days). The more controlled hydration rate of slag may contribute to reduced self-desiccation and a more stable pore structure, thereby limiting shrinkage (Neto et al., 2008; Vigor et al., 2024). For mixtures incorporating CC, shrinkage increased with higher CC replacement. IL-50CC exhibited the greatest shrinkage, indicative of significant pore-structure refinement driven by the high reactivity of metakaolin and associated self-desiccation (Afroz et al., 2023). For the IL-30CC mixture, shrinkage remained close to that of the IL mixture, although slightly elevated at early ages. The LC3 system showed shrinkage behavior between the IL and IL-30RCA. Notwithstanding, at 127 days, IL, IL-30CC, LC3, and IL-30RCA presented similar shrinkage.

Environmental Impact Assessment

Figures 19 and 20 present the GWP and CED results, respectively, for 1 yd^3 concrete incorporating various SCMs, with a detailed breakdown of contributions from each stage and ingredient. Compared with the materials-related effects, GWP and CED associated with manufacturing and transportation are significantly lower. However, GWP and CED of transportation in mixtures containing CC are slightly higher than those of the other mixtures, primarily because CC requires the longest transportation distance.

As expected, PLC is the primary contributor, accounting for 95.5% of GWP in the IL concrete due to its highest clinker content. In all concrete mixtures, the GWP contributions from other ingredients—that is, sand, coarse aggregate, water, and HRWR—are significantly lower because of the low carbon emissions of sand, coarse aggregate, and water, and the low dosage of HRWR. In mixtures with PLC partially replaced with SCMs, which have lower carbon emissions, GWP is significantly reduced. IL-50SC exhibits the lowest GWP (144.8 kg CO_2-eq), owing to its minimal PLC content and SC's relatively lower GWP. IL-50CC has a slightly higher GWP (159.3 kg CO_2-eq) due to the marginally greater carbon emissions of CC than SC. Despite RCA having the lowest carbon emission among the SCMs, IL-30RCA shows a slightly higher GWP (176.8 kg CO_2-eq) compared with LC3 (170.3 kg CO_2-eq) due to its higher PLC content. Although IL-30CC has the highest GWP (190.2 kg CO_2-eq) among mixtures incorporating SCMs, it still achieves a 20.1% reduction relative to PLC alone. When accounting for the GWP of transportation, the reduction in GWP for mixtures containing SCMs is slightly diminished because SCMs are sourced from outside Virginia, whereas the PLC is locally produced in Virginia. Despite the longer transportation distances required for SCMs, their use still achieves a 16 to 34% reduction in GWP, demonstrating that incorporating SCMs remains a worthwhile strategy for reducing environmental impacts.

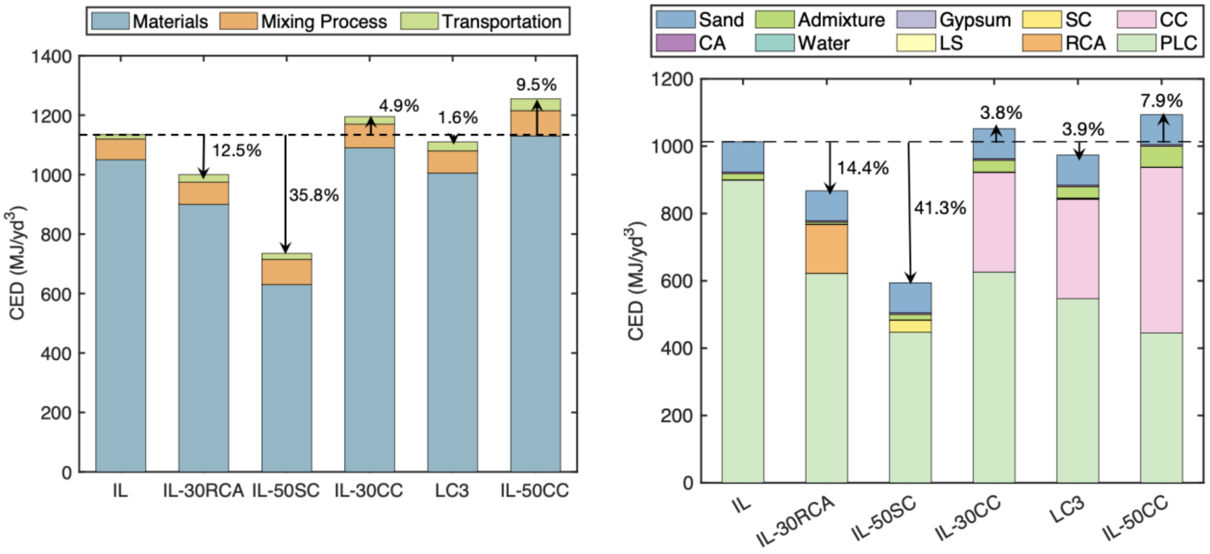
In Figure 19a, the shaded grey band represents the GWP range of ready-mixed concrete with a compressive strength of 5001–6000 psi, as reported in the National Ready Mixed Concrete Association (2022) LCA report. This range reflects ready-mixed concrete mixtures incorporating varying proportions of FA and SC. The upper bound corresponds to the mixture without SCMs (0% FA and SC), whereas the lower bound represents the mixture containing 50% FA and SC. It is evident that the GWP of the PLC-based concrete mixtures with SCMs developed in this study is less than the minimum GWP of the industrial ready-mixed concrete benchmark.



(a) **(b)**

Figure 19. GWP for Concrete with Various Supplementary Cementitious Materials of (a) Cradle-to-Gate System Boundary; (b) Materials Stage Only. CA = coarse aggregate; CC = calcined clay; GWP = global warming potential; IL = type IL cement; LC3 = limestone calcined clay cement; LS = limestone; PLC = Portland limestone cement; RCA = reclaimed coal ash (Class F); RMC = ready-mixed concrete; SC = slag cement.

In contrast, the CED of concrete incorporating CC generally shows a marginal increase, primarily due to the higher energy consumption associated with calcining clay for CC (Figure 20). As a result, concrete with the highest PLC replacement content exhibits the highest CED. In addition, although the dosage of HRWR is minimal, its energy consumption (28.5 MJ/kg) is 8 to 9 times greater than that of SCMs and PLC. Therefore, HRWR becomes the third primary contributor, especially in concrete incorporating CC, which requires more HRWR to achieve the desired workability. Similar to the GWP results, the CED contribution from water is negligible. LC3 exhibits a similar CED with the IL mixture, attributed to its relatively low clinker, CC, and HRWR contents. However, the energy consumption data for CC were obtained from the manufacturer, which currently operates at a pilot scale. Pilot-scale products generally exhibit higher carbon emissions compared with commercial-scale products because of inefficiencies in production, less optimized resource utilization, and less efficient logistics (Hetherington et al., 2014). Therefore, the energy consumption of CC can be further reduced by scaling up to commercial production levels. Furthermore, the LC3 binder utilized in this study is blended on site. If the LC3 binder were produced directly at the plant, its energy consumption could be further reduced because of shared kiln energy and process integration. The IL-30RCA mixture demonstrates a slightly lower CED, primarily attributed to the electricity consumption during the FA reclamation process. In contrast, the IL-50SC mixture exhibits a significantly reduced CED owing to its inherently low energy requirements.



(a) **(b)**

Figure 20. CED for Concrete with Various Supplementary Cementitious Materials of (a) Cradle-to-Gate System Boundary; (b) Materials Stage Only. CA = coarse aggregate; CC = calcined clay; CED = cumulative energy demand; IL = type IL cement; LC3 = limestone calcined clay cement; LS = limestone; PLC = Portland limestone cement; RCA = reclaimed coal ash (Class F); SC = slag cement.

Summary of Findings

Characterization of Cementitious Materials

- The two CCs evaluated in this study, CC-1 and CC-2, met all ASTM C618 Class N pozzolan chemical requirements assessed (all except moisture content). Both CCs significantly exceeded the minimum 7- and 28-day SAI requirements for Class N pozzolans per ASTM C618 when tested using a modified SAI method with a constant w/b rather than a constant flow (ASTM International, 2023a). Flow measurements indicated that CCs substantially reduce workability, whereas RCA improves workability and SC maintains workability similar to the control. R3 reactivity tests confirmed that CCs are substantially more reactive than RCA and exhibit reactivity more comparable with SC. Overall, results from the modified SAI test and R3 method showed good agreement.

Evaluation of the Properties of Concrete Incorporating LC2 and LC3 Systems

- To achieve the target slump (2–4 inches), concrete mixtures containing CC required substantially higher dosages of HRWR. This increased demand was attributed to the porous micromorphology and high surface area of the CC particles, which elevate water demand and reduce workability. For example, the LC2 mixture incorporating 30% CC (IL-30CC) and the LC3 mixture required roughly six times more HRWR than the control IL mixture. In contrast, the air-entraining behavior of mixtures incorporating CC was similar to the control, requiring comparable AEA dosages to achieve the target air content (5–8%). This trend differs significantly from the mixture with RCA, which required a lower HRWR dosage and a higher AEA dosage than the control to meet the same slump and air-content targets.

- At 7 days, the control IL mixture exhibited the highest compressive strength, whereas mixtures containing SCMs showed lower strengths because of clinker dilution. Among these mixtures, the LC2 mixture incorporating 30% CC (IL-30CC) and the mixture incorporating 50% SC (IL-50SC) demonstrated the strongest early-age performance, with only minor strength reductions relative to the IL mixture. By 28 days and beyond, both IL-30CC and IL-50SC outperformed the IL mixture and maintained this advantage through 196 days. The LC3 mixture and LC2 mixture with 50% CC (IL-50CC) also continued gaining strength beyond 90 days, ultimately slightly surpassing the IL mixture at 196 days. Although the mixture incorporating 30% RCA (IL-30RCA) exhibited the lowest early-age strengths, it gradually increased to reach values comparable with the IL mixture by 196 days. Overall, the IL-30CC and IL-50SC mixtures provided the best strength development among mixtures containing SCMs. Nonetheless, the LC3, IL-50CC, and even the IL-30RCA mixture demonstrated notable long-term strength gains, underscoring the potential of SCM-rich mixtures to achieve adequate strength performance over time.

- The elastic modulus results showed consistent stiffness gains across all mixtures from 28 to 196 days, indicating continued hydration and microstructural refinement. Mixtures containing SCMs exhibited slightly lower stiffness than the control at 28 days. By 196 days, IL-30CC, IL-RCA, and IL-50SC surpassed the control mixture, and LC3 and IL-50CC achieved comparable stiffness, suggesting enhanced long-term matrix development. These findings confirm that, even at high cement replacement levels, structural performance can be preserved while reducing clinker content.

- Rapid chloride permeability and resistivity test results showed that the IL control mixture maintained high chloride permeability at both 28 and 196 days, despite modest reductions from continued hydration. In contrast, mixtures with SCMs ranged from high to low permeability at 28 days and reached very low permeability by 196 days, indicating significant microstructure densification. Mixtures with CC and SC showed rapid reductions in permeability, whereas the RCA mixture required more time to reach very low levels. In addition, at 196 days, non-steady-state chloride migration tests indicated approximately 70 to 90% reduction in chloride migration coefficients for SCM-containing mixtures relative to the control, confirming their excellent long-term resistance to chloride penetration.

- Water permeability measurements further confirmed the beneficial effects of SCM incorporation in reducing concrete permeability, with initial and secondary sorptivity decreasing by approximately 30 to 85% and 60 to 75%, respectively. IL-50SC exhibited the greatest reduction in sorptivity, followed by IL-30CC. LC3 showed a slightly lower reduction compared with IL-30CC, although IL-30RCA presented the smallest sorptivity reduction among the mixtures containing SCMs.

- Drying shrinkage results showed that IL-30CC, LC3, and IL-30RCA exhibited shrinkage behavior similar to the control IL mixture. In contrast, IL-50SC demonstrated the lowest shrinkage, whereas IL-50CC showed the highest shrinkage.

- Table 7 qualitatively summarizes how the different cementitious binders affect concrete properties relative to the control IL mixture. Overall, the results indicate that LC3 or LC2 concrete containing 30% CC (i.e., IL-30CC) performs similarly to, or better than, the IL-30RCA mixture across all evaluated properties, except for workability, because mixtures with CC require a higher HRWR dosage. In addition, LC3 and IL-30CC generally exhibit comparable performance, with the primary distinction being that IL-30CC tends to develop strength slightly faster.

Table 7. Summary of Changes Relative to Control IL Mixture

Property	Standard	Age (Days)	Concrete Mixtures				
			IL-30CC	LC3	IL-30RCA	IL-50SC	IL-50CC
Slump	ASTM C143	N/A	🟥 ↓↓	🟥 ↓↓	🟩 ↑	↔	🟥 ↓↓
Air Content	ASTM C231	N/A	↔	↔	🟥 ↓	↔	↔
Compressive Strength	ASTM C39	7	↔	🟥 ↓	🟥 ↓	↔	🟥 ↓
		28	🟩 ↑	🟥 ↓	🟥 ↓	🟩 ↑	↔
		196	🟩 ↑	🟩 ↑	↔	🟩 ↑	↔
Permeability	ASTM C1202 AASHTO T358 NT Build 492	28	🟩 ↓↓	🟩 ↓↓	🟩 ↓	🟩 ↓↓	🟩 ↓↓
		196	🟩 ↓↓	🟩 ↓↓	🟩 ↓↓	🟩 ↓↓	🟩 ↓↓
Drying Shrinkage	ASTM C157	120	↔	↔	↔	🟩 ↓	🟥 ↑
Elastic Modulus	ASTM C496	28	↓	↓	↓	↔	↔
		196	↑	↔	↑	↑	↔

↔ = no meaningful change; ↑ = increase; ↓ = decrease; ↓↓ = large decrease; CC = calcined clay; IL = type IL cement; LC3 = limestone calcined clay cement; N/A = not applicable; RCA = reclaimed coal ash (Class F); SC = slag cement.

Environmental Impact Assessment

- GWP of concrete can be reduced by 23.1% when using LC3, while delivering performance comparable with concrete containing 30% Class F coal ash (i.e., IL-30RCA). Furthermore, the GWP reduction achieved with LC3 is similar to that of the IL-30RCA mixture. In contrast, using LC2 with 30% CC (i.e., IL-30CC) results in a 16.1% reduction in GWP, which is less than that achieved by LC3 or IL-30RCA. However, it provides improved performance. Overall, these GWP reductions remain significant even when accounting for the increased GWP associated with transporting CC over longer distances. Additional reductions can be realized by sourcing CC locally, thereby minimizing transportation-related emissions.

CONCLUSIONS

- *CCs in either LC3 or LC2 systems are suitable for VDOT concrete applications.* At a 30% CC dosage, concrete incorporating these cementitious systems achieved adequate early (7-days) and long-term (≥ 90 days) strength development along with very low permeability—performance that was comparable with or better than concrete containing a 30% replacement of Type IL cement with Class F coal ash. Accordingly, CCs can help alleviate shortages in FA supply. This is applicable for CCs meeting the requirements of ASTM C618 for Class N pozzolans.

- *When using CCs, admixture selection and dosage are critical for adequate workability during placement.* CCs produce a significant loss in slump and slump retention, which should be carefully considered to prevent issues during placement in the field. Increasing the mixing water to compensate for workability loss should be avoided because it increases the w/b ratio adversely affecting concrete properties.

- *Using LC3 lowers the GWP of concrete by an amount comparable with mixtures using a 30% replacement of Type IL cement with Class F coal ash, while delivering similar or better mechanical and durability properties. Using a 30% replacement of Type IL cement with CC, or LC2, results in a smaller GWP reduction but provides improved mechanical and durability characteristics*. These GWP values assume CC is sourced from outside Virginia because no local supply was available during the study. Additional GWP reductions will be realized using the upcoming Virginia CC source because transportation-related emissions will be reduced.

- *The literature reports excellent ASR mitigation performance for CCs, particularly at dosages of around 30%. However, ASR testing was outside the scope of this project, and the effective dosage for ASR mitigation in VDOT concretes should be verified experimentally.*

- *Although two CCs sourced in the United States and a laboratory-produced LC3 were evaluated in this study, there remains a need to test the actual commercial products that will be used in Virginia prior to implementation to verify their performance and to understand practical considerations such as specific admixture demand*. This step is important because different clay sources can exhibit different behaviors, and commercially produced LC3 may have variations in composition that affect performance. Nevertheless, the results of this study provide a valuable general understanding of how these materials are likely to perform.

RECOMMENDATIONS

1. *VDOT should allow for the use of CCs that meet the ASTM C618 requirements for Class N pozzolans in VDOT concretes*. A prescriptive table specifying the minimum effective dosage of CC needed to mitigate ASR for varying alkali loading in concrete using moderately reactive aggregates (i.e., R1 per ASTM C1778 (ASTM International, 2022c)) should be developed. Until such a table is available, when reactive aggregates are used—or when aggregate reactivity is uncertain—the intended CC dosage to be used in concrete should be evaluated for ASR mitigation. This evaluation should be conducted using either the modified AASHTO T 380 procedure or ASTM C1567 following the recommendations in VTRC Report 26-R29 (Behravan et al., 2026).

2. *VTRC should submit a research needs statement to the Concrete Research Advisory Committee to evaluate the upcoming Virginia IT cement incorporating CC in both the laboratory and the field.*

IMPLEMENTATION AND BENEFITS

The researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

Regarding Recommendation #1, VDOT's Materials Division with the support of the Structure and Bridge Division and VTRC, will incorporate CCs meeting the ASTM C618 requirements for Class N pozzolans as an SCM alternative for hydraulic cement concrete in the Supplement to the 2026 VDOT Road and Bridge Specifications (VDOT, unpublished) within 4 years of this report's publication date. Specific prescriptive and performance requirements for CCs and concrete will be defined.

Regarding Recommendation #2, VTRC will submit a research needs statement to the Concrete Research Advisory Committee to evaluate the upcoming Virginia IT cement incorporating CC in the laboratory and in the field within 1 year of this report's publication date.

Benefits

Implementing the recommendations from this study is expected to provide VDOT with a viable SCM alternative capable of mitigating seasonal or regional shortages of FA, thereby strengthening long-term material supply resilience. The use of locally produced SCMs, such as a Virginia CC, can also reduce long-distance material transport and lower GWP of concrete mixtures, supporting VDOT's sustainability goals. Expanding the portfolio of SCM options may additionally promote a more competitive market, potentially reducing costs—particularly when local sources are available. CCs also yield concrete with very low permeability, enhancing the durability and service life of VDOT structures. Furthermore, the knowledge generated on the performance of LC3 and LC2 systems prepares VDOT for emerging products such as IT cements incorporating CC, ensuring the agency is equipped to evaluate and implement new materials as they enter the market, especially in light of ongoing FA shortages. Collectively, these benefits can improve asset preservation, enable more efficient use of funds, and enhance the resilience of VDOT's infrastructure.

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