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# Effect of Carbon-Negative Carbon Black on Concrete Properties

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16. Abstract:

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The carbon black was found to consist almost entirely of elemental carbon with negligible reactivity, functioning as an inert filler rather than as a supplementary cementitious material. At the dosage evaluated, concrete incorporating carbon black can meet the Virginia Department of Transportation Class A4 General concrete fresh and hardened property requirements. However, its inclusion sharply increased admixture demand—approximately 1.5 to 2 times more high-range water reducer and 20 to 45 times more air-entraining admixture—reduced compressive strength by 8 to 23% (least with calcined clay), and slightly increased chloride-transport indices and drying shrinkage, while having minimal effect on elastic modulus and Poisson's ratio. Accordingly, carbon black provided no performance benefit beyond a possible reduction in embodied carbon, the magnitude of which depends strongly on the source of the carbon black. Carbon black may nevertheless offer transportation-relevant functionalities, such as self-heating for de-icing and self-sensing for structural monitoring; however, these effects generally require higher dosages than those considered in this study.

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**FINAL REPORT**

# EFFECT OF CARBON-NEGATIVE CARBON BLACK ON CONCRETE PROPERTIES

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## ABSTRACT

Carbon black is a fine, electrically conductive carbon-based material that can be produced from captured carbon dioxide, generating interest in potentially carbon-negative carbon black as an additive for lower-carbon concrete. This study characterized carbon black and evaluated the fresh, hardened, and durability properties of the Virginia Department of Transportation Class A4 General concrete produced with different cementitious binder systems with and without carbon black. Six concrete mixtures were prepared: three reference mixtures using Type IL cement alone or with reclaimed Class F coal ash or calcined clay as supplementary cementitious materials at 30% cement replacement by mass; and three carbon black-modified counterparts incorporating carbon black at 3% cement replacement by mass. Carbon black was characterized by particle-size analysis, scanning electron microscopy with energy-dispersive spectroscopy, and reactivity testing. The concretes were evaluated for slump, air content, unit weight, compressive strength, elastic modulus and Poisson's ratio, surface resistivity, rapid chloride permeability, non-steady-state chloride migration, and drying shrinkage.

The carbon black was found to consist almost entirely of elemental carbon with negligible reactivity, functioning as an inert filler rather than as a supplementary cementitious material. At the dosage evaluated, concrete incorporating carbon black can meet the Virginia Department of Transportation Class A4 General concrete fresh and hardened property requirements. However, its inclusion sharply increased admixture demand—approximately 1.5 to 2 times more high-range water reducer and 20 to 45 times more air-entraining admixture—reduced compressive strength by 8 to 23% (least with calcined clay), and slightly increased chloride-transport indices and drying shrinkage, while having minimal effect on elastic modulus and Poisson's ratio. Accordingly, carbon black provided no performance benefit beyond a possible reduction in embodied carbon, the magnitude of which depends strongly on the source of the carbon black. Carbon black may nevertheless offer transportation-relevant functionalities, such as self-heating for de-icing and self-sensing for structural monitoring; however, these effects generally require higher dosages than those considered in this study.

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## INTRODUCTION

The cement industry plays a significant role in global greenhouse gas emissions, accounting for approximately 5 to 8% of total emissions (Kalt et al., 2022). The main source of emissions is associated with the production of clinker, which is the main constituent (> 90% by mass) of ordinary Portland cement. Consequently, extensive research efforts have been directed toward reducing the amount of clinker in cement or reducing overall cement usage in concrete while maintaining the requisite strength and durability. Traditionally, a widely used approach to reduce cement content in concretes involves utilizing supplementary cementitious materials (SCMs), such as coal ash (mainly fly ash) and slag cement, which can substitute for a significant amount of cement. However, availability of conventional SCMs is beginning to dwindle in the United States, making it necessary to look at alternatives.

Efforts to reduce the use of clinker in cement have recently led to the wide adoption of Portland limestone cement in the United States. Portland limestone cement is included in ASTM C595 blended cement standard as Type IL, which allows for the replacement of 5 to 15% of the Portland cement clinker with limestone powder that is interground with the clinker (ASTM International, 2025a). This adaptation results in a reduction of the cement's carbon footprint while keeping concrete performance similar to that of concrete using ordinary Portland cement, particularly when incorporating SCMs (Berke et al., 2022). Although limestone is abundant, incorporating more than 10% of it into cement can increase porosity, degrading the properties of concrete (Barbhuiya et al., 2023). In contrast, blends of clinker, calcined clay (CC), limestone, and gypsum, known as limestone calcined clay cement (LC3), have demonstrated significant promise as a suitable alternative to further reduce the use of clinker. LC3 systems have been extensively studied for their potential in low-carbon cement production outside the United States. Laboratory experiments have successfully produced a satisfactorily performing LC3 blend with up to 50% clinker substitution, leading to a 40% reduction in carbon dioxide ($CO_2$) emissions

(Scrivener et al., 2018). This LC3 blend is regarded as the "standard" composition, consisting of 50% clinker, 30% CC, 15% limestone, and 5% gypsum. LC3 is classified under ASTM C595 as a Type IT cement, specifically IT(P30)(L15), in which the pozzolan component (i.e., P30) is CC (ASTM International, 2025a). Importantly, LC3 constituents are widely available worldwide, making their large-scale implementation feasible. A major challenge for LC3 adoption lies in the substantial financial investment required by cement producers to manufacture the new cement. LC3 production demands dedicated infrastructure, such as a separate kiln line or a flash calciner, leading to considerable financial commitments (Kanagaraj et al., 2023; Krishnan et al., 2018; Scrivener et al., 2018). Notwithstanding, with the availability of Type IL cement—which already contains clinker, limestone, and gypsum—a viable alternative in the near term is the production of LC3-like systems known as LC2 by simply mixing Type IL cement with CC at a ready-mix plant. In contrast to LC3, LC2 offers a more adaptable alternative that does not demand extensive infrastructure, providing flexibility within existing cement production processes. Importantly, CCs are expected to become a major source of alternative SCMs in the long term. Furthermore, a Virginia-produced LC3 product is expected to be available on the market by 2029.

Historically, significant amounts of coal ash (e.g., fly ash and bottom ash) were not utilized and were disposed of in landfills and surface impoundments (Diaz-Loya et al., 2019). Landfill-stored coal ash typically contains low moisture levels, added for compaction and dust containment. For use in concrete, landfill coal ash can be processed to meet ASTM C618 specifications (ASTM International, 2025b; Diaz-Loya et al., 2019). This type of coal ash is referred to as reclaimed or harvested coal ash. Recent studies have shown that reclaimed coal ash (RCA) can perform similarly to conventional Class F fly ash because landfill environments do not provide the highly alkaline conditions required for the reaction of these ashes, allowing them to remain pozzolanic (Diaz-Loya et al., 2019; Subedi et al., 2022). RCA is expected to be a significant alternative SCM source for the short to mid-term, helping in the production of sustainable concrete.

Another pathway to reducing the carbon footprint of concrete involves incorporating novel carbon-negative additives. Biochar, a charcoal-like material produced through the pyrolysis of organic matter, has recently gained significant attention as a means to substantially lower the carbon footprint of concrete (Hamidi and Tunstall, 2025; Sirico et al., 2021). A less explored alternative is carbon black (CB), produced via the Noyes process, which has the potential to be carbon negative (Noyes, 1985; Solid Carbon Products, 2022). Other forms of CB have been investigated in cementitious systems—primarily in cement paste and mortar—with the aim of imparting electrical functionalities, such as piezoresistivity (i.e., changes in electrical resistance under mechanical stress) to enable self-sensing for structural health monitoring, or electrical conductivity for resistive (Joule) heating (i.e., conversion of electrical energy into heat) to support self-heating de-icing applications (Dinesh et al., 2023; Monteiro et al., 2017; Soliman et al., 2020; Stefaniuk et al., 2025). Through the Noyes process, CB can be produced by combining $CO_2$ with hydrogen or methane, providing a pathway to convert industrial $CO_2$ emissions into solid carbon products (Noyes, 1985; Solid Carbon Products, 2022). When coupled with renewable energy and low-carbon hydrogen, this process can achieve a carbon-negative footprint. The use of Noyes-derived CB, however, has not been widely evaluated, particularly on concrete mixtures relevant to state departments of transportation. This study evaluates novel

binder systems incorporating Type IL cement, alternative SCMs such as CC and RCA, and Noyes-derived CB in the Virginia Department of Transportation (VDOT) relevant concrete mixtures. The objective is to reduce embodied carbon while maintaining the fresh, mechanical, and durability performance required for transportation infrastructure applications.

## PURPOSE AND SCOPE

The purpose of this study was to explore the feasibility of integrating Type IL cement with alternative SCMs (CC and RCA) and CB to produce concrete materials with a reduced carbon footprint while maintaining the necessary workability, strength, and durability characteristics. The specific objectives of the study were to:

- Characterize CB.
- Evaluate the fresh, hardened, and durability properties of VDOT Class A4 General concrete incorporating the different cementitious binder systems.

## METHODS

### Overview

This research project consisted of three tasks to achieve the main research objective. The following research tasks are described in detail in the subsequent sections:

1. Literature review.
2. Characterization.
3. Evaluation of the concrete properties.

### Literature Review

A literature review on the use of CB in cementitious systems was conducted to support and guide the research activities in this project.

### Characterization

#### Materials

A locally available Type IL cement (IL), containing approximately 14.4% limestone and 4% gypsum, was used in this study. CC from Georgia and RCA meeting ASTM C618 Class F coal ash requirements from North Carolina were used in this study. The CB evaluated was procured from a U.S. manufacturer that produced it through the Noyes process. The specific gravities, obtained from the manufacturers, of IL, CC, RCA, and CB were 3.07, 2.74, 2.34, and 1.49, respectively. Figure 1 presents images of the SCMs and CB considered in this study.



**(a)** **(b)** **(c)**

**Figure 1. Supplementary Cementitious Materials and Carbon Black Considered in this Study: (a) Reclaimed Coal Ash (Class F); (b) Calcined Clay; (c) Carbon Black (as received)**

Table 1 reports the chemical oxide compositions of the cement and SCMs, as characterized in a previous study by this study's principal investigator (Arce et al., 2026).

**Table 1. Oxide Chemical Composition of IL, CC, and RCA**

| Component | IL | CC | RCA |
|---|---|---|---|
| $SiO_2$ | 16.81 | 47.33 | 53.94 |
| $Al_2O_3$ | 3.79 | 46.67 | 30.08 |
| $Fe_2O_3$ | 3.27 | 1.88 | 7.84 |
| CaO | 68.01 | 0.33 | 1.08 |
| $Na_2O$ | 0.07 | 0.06 | 0.29 |
| $K_2O$ | 0.79 | 0.12 | 3.43 |
| $SO_3$ | 3.61 | 0.06 | 0.07 |
| $SiO_2$+$Fe_2O_3$+$Al_2O$ (%) | 23.87 | 95.88 | 91.86 |
| Total Alkali (%$Na_2O_{eq}$) | 0.59 | 0.14 | 2.55 |
| Loss on Ignition (%) | 1.00 | 0.96 | 0.46 |

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

Prior to using it in concrete, CB was mechanically processed using a ball mill for 2 hours to reduce particle agglomeration, reduce particle size, and improve dispersion within the cementitious matrix. Because CB can soak up significant amounts of water, its water absorption capacity was evaluated using the tea bag method (Gupta et al., 2018; Mensah et al., 2024). In this procedure, a known mass of CB was enclosed in a permeable tea bag, immersed in water for 24 hours, and weighed after removing excess surface moisture. CB absorbed approximately 3.1 grams of water per gram of dry CB (i.e., 310% absorption) within the first 15 minutes, and the absorption remained nearly constant through 1,440 minutes. This rapid and high-water uptake confirmed that the material could remove a substantial amount of free water during mixing if used in a dry condition. Therefore, CB was preconditioned to a saturated surface dry (SSD) state before mixture proportioning, using an approach similar to that used for lightweight aggregates, so that absorbed water was accounted for separately from the effective mixing water. The milled CB in SSD condition was used in concrete to prevent unintended reductions in the effective water to cementitious materials ratio (w/cm) during mixing. Figure 2 shows the milled CB in SSD condition prior to dosing it to concrete.



**Figure 2. Milled Saturated Surface Dry Noyes Carbon Black Used in Concrete**

### Particle Size Distribution

The particle size distributions of the cement, SCMs, and CB were measured using a laser diffraction particle size analyzer.

### Scanning Electron Microscopy and Energy Dispersive Spectroscopy

The surface morphology and chemical elemental composition of CB were analyzed using a FEI Quanta 650 scanning electron microscope equipped with an Oxford AZtech energy dispersive spectroscopy detector. To enhance conductivity and improve image contrast, a thin layer of gold was sputter-coated onto the samples under vacuum conditions before imaging.

### Reactivity

To evaluate the reactivity of the selected SCMs and CB, ASTM C1897 Method A was employed (ASTM International, 2020). In this 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 to simulate the chemical environment in cement paste. 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.

## Evaluation of the Concrete Properties

### Concrete Mixture Design and Sample Preparation

Six VDOT Class A4 General concrete mixtures were designed to evaluate the effect of the different cementitious binder systems on the concrete properties. The binder systems

evaluated were IL, IL-30RCA, and IL-30CC, as reference mixtures, and IL-3CB, IL-30RCA-3CB, and IL-30CC-3CB, as the CB-modified counterparts. Only 3% CB content was selected for evaluation to prevent excessive demand for admixtures, given the findings from preliminary testing in the cementitious mortars.

In accordance with the requirements for Class A4 General concrete in VDOT's (2020) *Road and Bridge Specifications*, mixtures used the maximum w/cm of 0.45, the minimum cementitious content of 635 lb/yd$^3$, and a nominal maximum aggregate size of 1 inch (ASTM C33 compliant #57 granite coarse aggregate) (ASTM International, 2024a). The sand used was natural silica concrete sand (ASTM C33 compliant). The SSD specific gravities of the coarse and fine aggregates were 2.80 and 2.65, respectively. The target slump and air content were 2 to 4 inches and 6.5 ± 1.5%, respectively, per VDOT's specifications. To achieve these targets, a polycarboxylate-based high-range water reducer (HRWR) and an air-entraining admixture (AEA) were used to adjust the slump and air content. Table 2 provides detailed mixture proportions considering SSD aggregates and CB.

**Table 2. 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) | |
|---|---|---|---|---|---|---|---|---|---|
| | IL | RCA | CC | CB | Coarse | Fine | | AEA | HRWR |
| **IL** | 635 | 0 | 0 | 0 | 1,789 | 1,172 | 286 | 0.48 | 1.45 |
| **IL-30RCA** | 445 | 191 | 0 | 0 | 1,759 | 1,152 | 286 | 0.96 | 0.10 |
| **IL-30CC** | 445 | 0 | 191 | 0 | 1,776 | 1,163 | 286 | 0.36 | 5.68 |
| **IL-3CB** | 616 | 0 | 0 | 19 | 1,780 | 1,166 | 286 | 21.50 | 2.46 |
| **IL-30RCA-3CB** | 426 | 191 | 0 | 19 | 1,747 | 1,141 | 286 | 22.17 | 0.22 |
| **IL-30CC-3CB** | 426 | 0 | 191 | 19 | 1,763 | 1,155 | 286 | 7.13 | 8.23 |

AEA = air-entraining admixture; CB = saturated surface dry ground carbon black; CC = calcined clay; HRWR = high-range water reducer; IL = Portland limestone cement; RCA = reclaimed coal ash (Class F).

Concrete was prepared following ASTM C192 using a 13-gallon pan mixer (ASTM International, 2026a). The coarse aggregate, one-half of the mixing water (with dissolved AEA), and admixtures were added before starting the mixer. Sand, cementitious materials, and the remaining water were then added in sequence. After all the water was incorporated, the mixture was blended for 3 minutes, allowed to rest for 3 minutes, and then mixed for an additional 2 minutes. Following the mixing procedure, slump and air content were measured. If target slump and air content values were not achieved, additional HRWR or AEA were added to the mix, and the concrete was mixed for approximately 5 minutes. This process was repeated until the desired slump and air contents were achieved. On completing mixing, specimens were cast for testing.

## Fresh Properties

Fresh concrete properties, including slump (ASTM C143), unit weight (ASTM C138), and air content (ASTM C231), were evaluated for all mixtures (ASTM International, 2024b, 2026b, 2026c). Fresh properties reported are those of the mixtures prior to specimen casting, which was 30 minutes from water addition in nearly all cases.

### Compressive Strength

Compressive strength tests (ASTM C39) were performed on 4 × 8-inch cylindrical specimens at 7, 28, and 91 days (ASTM International, 2026d). Two 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 (ASTM C469) were performed on 4 × 8-inch cylindrical specimens at 7, 28, and 91 days (ASTM International, 2022). Two 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).

### Surface Resistivity

Surface resistivity (AASHTO T358) was measured on 4 × 8-inch cylindrical specimens at 7, 28, 56, and 91 days (American Association of State Highway and Transportation Officials, 2023). Two 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 per ASTM C1202, following the accelerated curing regime (ASTM International, 2025c). Two 4 × 8-inch cylindrical specimens were cured for 7 days in the moisture room in accordance with ASTM C511 (ASTM International, 2021), followed by 21 days in limewater at 100°F. After the curing period, 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, 2025c).

### Non-Steady-State Chloride Migration

The non-steady-state chloride migration test was conducted in accordance with NT Build 492 (1999) after 196 days of curing. This test determines the chloride migration coefficient, indicating how quickly chloride ions move through concrete when an external electric field is applied. Unlike the rapid chloride permeability test, which depends solely on electrical readings, this method directly measures chloride transport by assessing how deep the ions penetrate. A 4 × 8-inch cylindrical specimen was cured in limewater in accordance with ASTM C511 until the testing age (ASTM International, 2021). Next, three 2-inch slices were cut and conditioned following NT Build 492 prior to testing. The top and bottom 1 inch of the specimen were discarded. After testing, specimens were split and sprayed with silver nitrate solution to determine the chloride penetration depth.

### Drying Shrinkage

Drying shrinkage was evaluated in accordance with ASTM C157 on 3 × 3 × 11.25-inch prism specimens (ASTM International, 2024c). Samples were demolded at 23.5 ± 0.5 hour and soaked in limewater for at least 30 minutes, and then researchers recorded their initial comparator readings. After 7 days of curing in the moisture room in accordance with ASTM C511 (ASTM International, 2021), 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 1, 4, 7, 14, 28, 56, and 91 days of drying.

Table 3 provides a summary of the experimental program for the concrete mixtures evaluated.

**Table 3. 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 | 4x8-in. cylinder | Moist room | 2 each at 7, 28, and 91 days |
| Modulus of Elasticity | ASTM C469 | 4x8-in. cylinder | Moist room | 2 each at 7, 28, and 91 days |
| Surface Resistivity | AASHTO T358 | 4x8-in. cylinder | Limewater | 2 each at 7, 28, 56, and 91 days |
| Chloride Permeability | ASTM C1202 | 4x2-in. slice from 4x8-in. cylinder | Accelerated | 2 each at 28 days |
| Chloride Migration Coefficient | NT Build 492 | 4x2-in. slice from 4x8-in. cylinder | Limewater | 3 each at 196 days |
| Sorptivity | ASTM C1585 | 4x2-in. slice from 4x8-in. cylinder | Limewater | 3 each at 196 days |
| Length change | ASTM C157 | 3x3x11.25-in. prism | Limewater for 7 days, then dry room | 3 each at 1, 4, 7, 14, 28, 56, and 91 days of drying |

N/A = not applicable.

## RESULTS AND DISCUSSION

### Literature Review

CB is a carbonaceous material produced by partial combustion or pyrolysis of hydrocarbons, yielding fine elemental carbon particles with quasi-graphitic microstructure (Rosner et al., 2024). It is used in a wide range of applications, including rubber reinforcement for car tires (its dominant use, about 65% of consumption), mechanical rubber goods, plastics, paints and coatings, and battery and fuel-cell electrodes, among others (Rosner et al., 2024). Industrially, CB is produced through several routes—furnace, thermal, channel, and acetylene black—with the modern oil-furnace process dominating global production at more than 95% market share (Rosner et al., 2024). The global warming potential (GWP) reported for CB in the literature generally spans 0.78 to 5.25 kg $CO_2$eq/kg of CB, with acetylene black providing the lowest emissions but at a higher cost (Rosner et al., 2024). Relative to Type IL cement, whose GWP is approximately 0.84 kg $CO_2$eq/kg based on the U.S. industry average, these CB values

are relatively high and would provide little to no environmental advantage when used as an additive in concrete (Portland Cement Association, 2023). However, Noyes CB is produced from $CO_2$ by reaction with hydrogen or methane, yielding solid carbon and water (Noyes, 1985; Solid Carbon Products, 2022).

For the hydrogen pathway (Equation 1), a stoichiometric mass balance shows that 1 kg of solid carbon fixes 3.67 kg of $CO_2$ (the ratio of the molar masses of $CO_2$ and carbon, 44/12). The theoretical lower limit of GWP for CB produced through this route is therefore -3.67 kg $CO_2$eq/kg of CB—strongly carbon negative relative to the embodied carbon of Type IL cement, whose industry-average GWP is approximately 0.84 kg $CO_2$eq/kg of cement.

$$CO_2 + 2H_2 \rightarrow C + 2H_2O \quad \text{(Equation 1)}$$

At such a carbon-negative value, replacing roughly 20% of Type IL cement by mass with CB would, in principle, offset the binder's embodied carbon and approach a carbon-neutral concrete. This idealization assumes net-zero energy input and a net-zero-carbon hydrogen source, which is not realistic today. In practice, the embodied carbon of the hydrogen feedstock and process energy can offset much—or all—of this benefit, yielding outcomes that range from carbon negative to carbon positive. To the authors' knowledge, no third-party-verified lifecycle assessment currently exists to support a carbon-negative classification for a commercially produced Noyes CB. Nonetheless, producing carbon-negative Noyes CB is theoretically achievable and could provide a valuable pathway for lowering the embodied carbon of cement and concrete. Another challenge is the ability to incorporate large amounts of CB in cementitious materials.

CB has been widely studied in cementitious materials as a means of imparting additional functionalities, such as self-sensing, self-heating (de-icing), energy storage, and electromagnetic shielding (Chanut et al., 2023; Monteiro et al., 2017; Stefaniuk et al., 2025; Wu et al., 2025; Zhang et al., 2022). These functionalities typically rely on increasing the electrical conductivity of the material, a role that CB fulfills effectively because of its intrinsic high electrical conductivity (Zhang et al., 2022). Monteiro et al. (2017) reported that, in cementitious mortars, incorporating CB at a dosage of up to 4% (by mass of the cement) can enhance mechanical performance, whereas higher dosages of 7 to 10% are more suitable for enabling sensing capabilities. Soliman et al. (2020) reported that cement pastes and mortars begin to exhibit percolation-induced increases in electrical conductivity and associated resistive (Joule) heating at CB volumetric dosages of approximately 3 to 4%, which are critical for enabling both self-sensing and self-heating functionalities. Gwon et al. (2023) evaluated the use of CB (0–1.2 vol.%) and carbon fibers (0–0.4 vol.%) as conductive additives in cement pastes to enable self-heating behavior. The materials exhibited increased heating capacity up to a CB dosage of 0.8 vol.% because of poor particle dispersion at higher dosages. Although reductions in compressive strength were reported with increasing CB content, the mixtures also required higher amounts of water to maintain workability. As a result, the strength decrease cannot be attributed solely to CB because the change in the w/cm ratio acts as a confounding factor. Wu et al. (2025) investigated the effects of CB (at a dosage of 0–4% by mass of cement) on the microstructure and electromagnetic properties of cement mortars. Their results showed that although CB had minimal influence on total porosity, it reduced the proportion of large pores,

indicating a refined pore structure. Despite this refinement, compressive strength decreased with increasing CB dosage. In addition, the study identified a 3% cement-replacement level as the critical threshold at which significant changes in electrical properties emerged. Klyuev et al. (2024) investigated using CB in cement mortar at dosages of 4 to 12% by mass of cement. Two approaches to delivering CB into the mortar were evaluated, both aimed at improving CB dispersion: premixing CB into an aqueous suspension with a superplasticizer (polycarboxylate-based) and granulating CB with a superplasticizer before adding it to the dry mix. They concluded that granulating CB is the more effective incorporation method because it mitigates the strength reduction associated with CB addition. Wang et al. (2024) investigated using chemical dispersants to improve the heating efficiency (for de-icing), workability, and mechanical performance of nano CB-modified cement paste, whose effectiveness is limited by nano CB's tendency to agglomerate. Three dispersants—polycarboxylate superplasticizer, tannic acid, and sodium dodecyl sulfate—were evaluated. Sodium dodecyl sulfate was the most effective at dispersing nano CB, followed by tannic acid and then the polycarboxylate superplasticizer. The authors concluded that appropriate dispersant selection is an effective way to improve both the mechanical and functional (de-icing) performance of nano CB-modified cement paste.

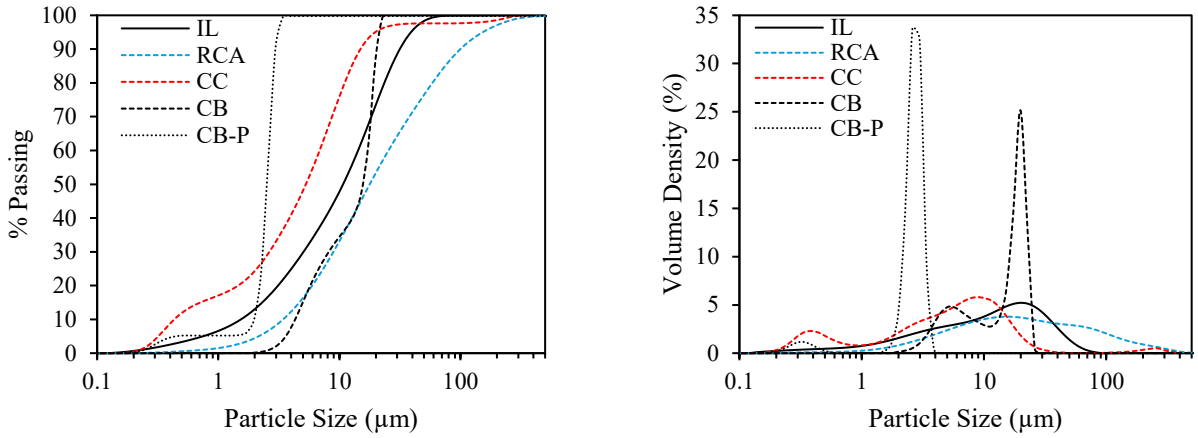
The literature shows that CB is a versatile conductive admixture that can endow cementitious materials with distinct electrically based functionalities by forming a conductive network within the hydrated cementitious matrix once a critical percolation threshold is reached. Three constraints recur. CB reduces workability, it tends to lower strength at functionally useful dosages, and its performance depends strongly on dispersion, which can be improved through appropriate delivery methods and the use of dispersants. Beyond these constraints, the environmental benefit of CB-bearing concrete remains contingent on the carbon footprint of CB production.

## Characterization of Cementitious Materials

### Particle Size Analysis

Figure 3 presents the particle size distribution of the cementitious materials. The particle size distributions of IL, RCA, and CC were obtained from a previous report by the principal investigator using the same materials (Arce et al., 2026). Data for the as-received CB and processed CB were collected during this study.

In Figure 3, it is observed that the as-received CB presented a narrow particle size distribution with a median particle size of 15.6 μm. Conversely, after processing, the CB presented a median particle size of 2.5 μm, demonstrating the effect of grinding in significantly reducing the particle size. IL, RCA, and CC displayed a median particle size of 10.7, 17.8, and 5.3 μm, respectively, with much broader particle size distributions than those of the as-received and processed CB.

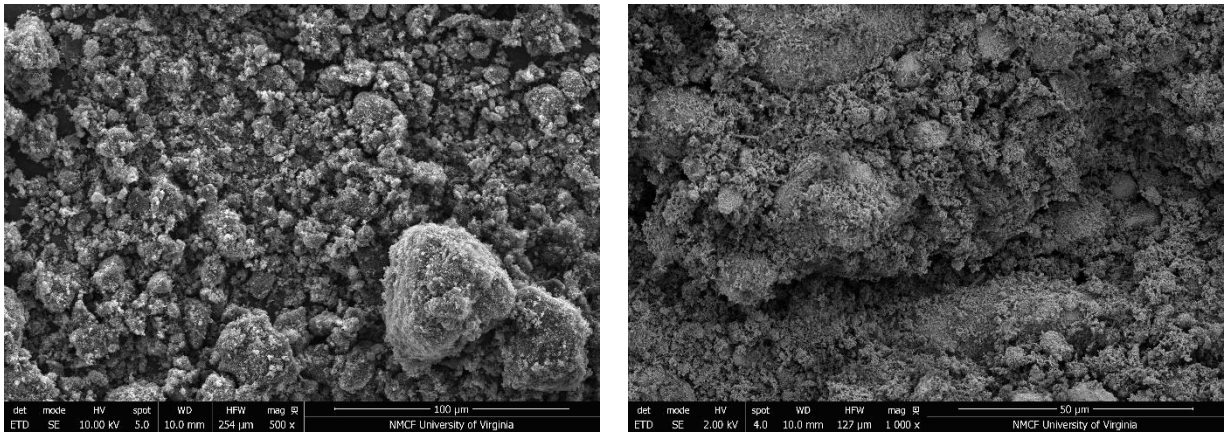



**(a)** **(b)**

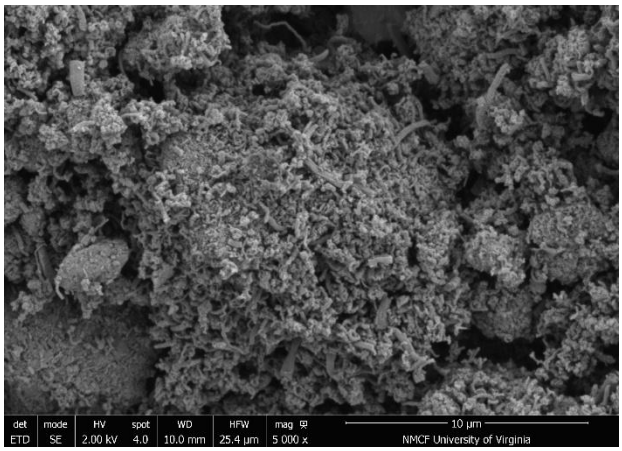
**Figure 3. Particle Size Distribution: (a) Cumulative Percent Passing Curves; (b) Volume Density Distributions. CB = carbon black (as received); CB-P = carbon black (processed); CC = calcined clay; IL = Type IL cement; RCA = reclaimed coal ash (Class F).**

## Scanning Electron Microscopy and Energy Dispersive Spectroscopy Results

Figure 4 shows the micromorphology of CB at different magnifications. CB exhibits a highly irregular micromorphology characterized by loosely bound agglomerates composed of mostly fine, rough-surfaced particles. At lower magnifications (Figure 4a), the material appears as large clusters with significant size variability, ranging from compact, rounded masses to more open, porous structures. As magnification increases (Figures 4b and 4c), the surfaces reveal dense networks of submicron features, including intricately textured, fiber-like or fragmented structures that interlock to form a highly complex microstructure.



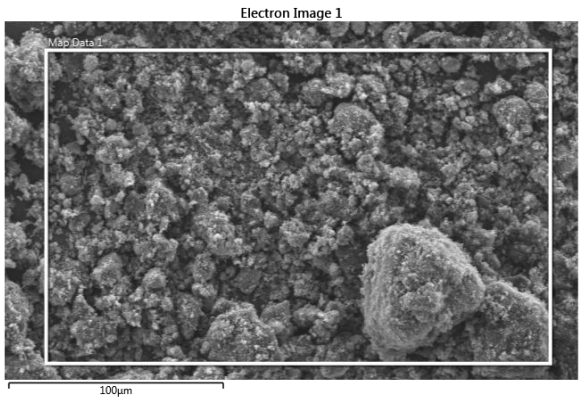

**(a)** **(b)**



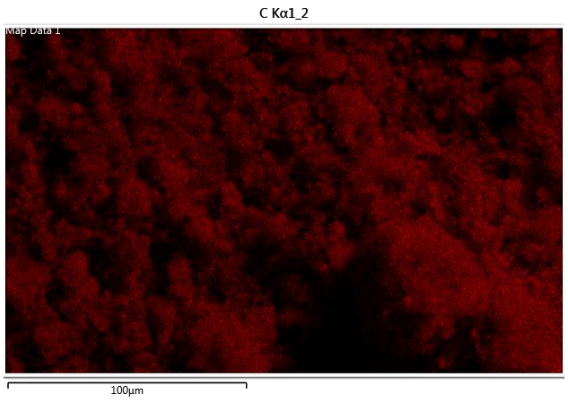

**(c)**

**Figure 4. Scanning Electron Microscopy Images Showing Morphology of Carbon Black: (a) 500x; (b) 1000x; (c) 5000x**

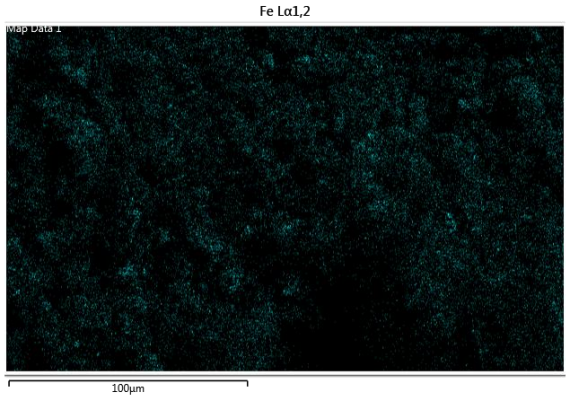
Energy Dispersive X-ray Spectroscopy (EDS) analysis was conducted to determine the chemical composition of CB. Figure 5 presents the EDS results. CB is primarily composed of carbon (approximately 86.2% by mass). In addition, small, uniformly distributed iron-bearing particles—presumably iron oxide—are observed (Figure 5c). Aluminum-containing particles are also detected; however, these particles occur in a few larger agglomerates, likely corresponding to alumina (Figure 5d).



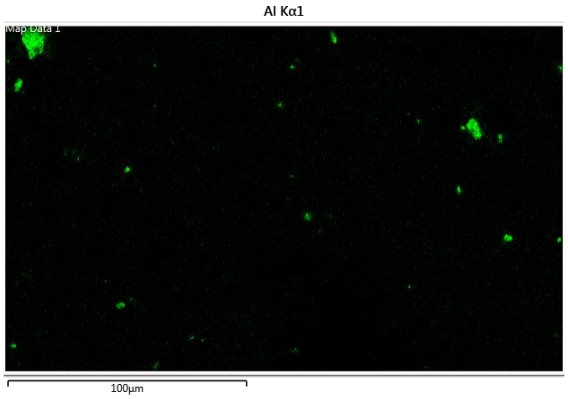

**(a)**



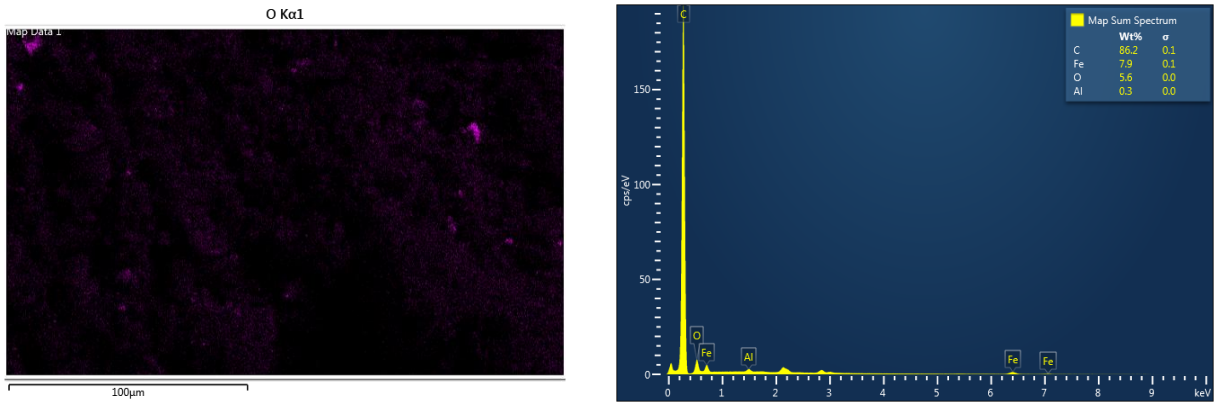

**(b)**




**(c)**




**(d)**




**(e)** **(f)**

**Figure 5. Energy Dispersive X-ray Spectroscopy, or EDS, Map of Carbon Black: (a) Map Area; (b) Carbon Distribution; (c) Iron Distribution; (d) Aluminum Distribution; (e) Oxygen Distribution; (f) Map Spectrum**

## Reactivity Test Results

Figure 6 presents the 7-day cumulative heat of hydration for the SCMs and CB materials evaluated in this study in accordance with the ASTM C1897 SCM reactivity test (ASTM International, 2020). CC exhibited the highest 7-day cumulative heat at 333 J/g of SCM, followed by RCA at 151 J/g of SCM. According to the RILEM TC 267-TRM report, fly ashes and CCs typically exhibit 7-day cumulative heat values of 160-360 J/g of SCM and 250-960 J/g of SCM, respectively (Londoño-Zuluaga et al., 2022). Thus, both materials showed heat values generally consistent with the literature, although the RCA value was slightly on the lower end.

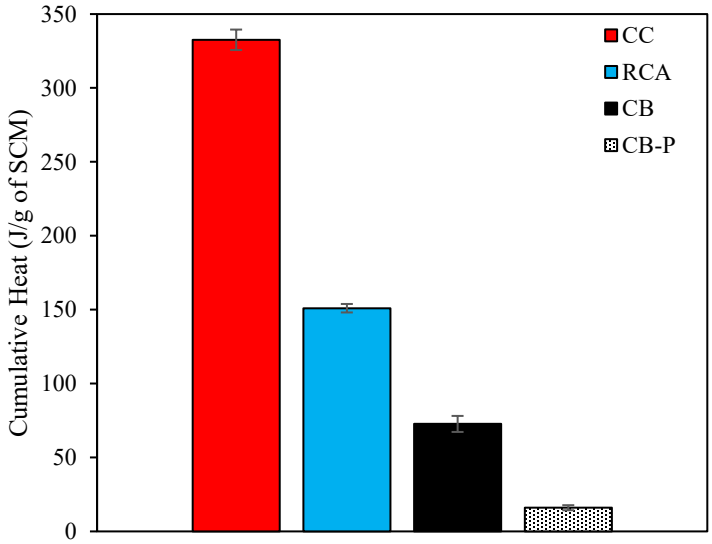



**Figure 6. 7-Day Cumulative Heat of Hydration of SCMs and CBs. CB = carbon black (as received); CB-P = carbon black (processed); CC = calcined clay; RCA = reclaimed coal ash (Class F); SCM = supplementary cementitious material.**

In contrast, the as-received CB and processed CB exhibited cumulative heat values of 73 and 16 J/g of SCM, respectively—values characteristic of materials that are largely inert. Based on the literature, cumulative heat values above ~100 J/g of SCM indicate potentially reactive

materials capable of qualifying as SCMs (Londoño-Zuluaga et al., 2022). Accordingly, the CB materials evaluated in this study do not exhibit the reactivity expected of an SCM and should primarily function as filler materials.

Interestingly, the coarser as-received CB presented a higher cumulative heat than the finer processed CB. The reason for this behavior is not fully understood; however, this observation does not have significant practical implications because both materials clearly lack the reactivity required to be considered SCMs.

## Evaluation of the Concrete Properties

### Concrete Fresh Properties

Table 4 summarizes fresh concrete properties, including slump, air content, and unit weight, along with the corresponding admixture dosages used to achieve these characteristics. For all mixtures except IL-3CB, the reported values correspond to measurements taken 30 minutes after adding water. For the IL-3CB mixture, results were recorded at 60 minutes after adding water. This deviation occurred because of the lack of prior experience with CB, which required multiple additions of AEA to achieve the target air content for A4 General concrete of 6.5 ± 1.5% in accordance with VDOT's (2020) *Road and Bridge Specifications*. Figure 7 shows images of the consistency of the concrete mixtures before molding.

From the results, all mixtures satisfied the slump and air content requirements for VDOT Class A4 General concrete (2–4 inches slump and 6.5 ± 1.5% air). However, the required admixture dosages varied substantially. Mixtures incorporating CB required approximately 1.5 to 2 times more HRWR to achieve comparable workability relative to mixtures without CB. Despite this increase, HRWR dosages generally remained within the typical range recommended by the admixture manufacturer.

In contrast, CB-containing mixtures required significantly higher AEA dosages, approximately 20 to 45 times greater than those used in mixtures without CB, to achieve the target air content. These dosages far exceed the typical ranges recommended by the admixture manufacturer. The only exception was the IL-30CC-3CB mixture, for which the AEA dosage was near the upper bound of recommended values.

**Table 4. Summary of Fresh Properties Immediately Before Molding the Specimens**

| Mix ID | Slump, in. (ASTM C143) | Air Content, % (ASTM C231) | Unit Weight, lb/ft³ (ASTM C138) | AEA[a] | HRWR[a] |
|---|---|---|---|---|---|
| **IL** | 3.25 | 6.5 | 146.1 | 0.48 | 1.45 |
| **IL-30RCA** | 2.75 | 6.2 | 145.6 | 0.96 | 0.10 |
| **IL-30CC** | 2.50 | 6.0 | 146.4 | 0.36 | 5.68 |
| **IL-3CB** | 3.00 | 6.8 | 154.6 | 21.50 | 2.46 |
| **IL-30RCA-3CB** | 4.00 | 6.0 | 145.2 | 22.17 | 0.22 |
| **IL-30CC-3CB** | 2.00 | 6.7 | 144.0 | 7.13 | 8.23 |

AEA = air-entraining admixture; CB = carbon black; CC = calcined clay; HRWR = high-range water reducer; RCA = reclaimed coal ash. [a]Dosage in fluid ounces per 100 pounds of cementitious materials.

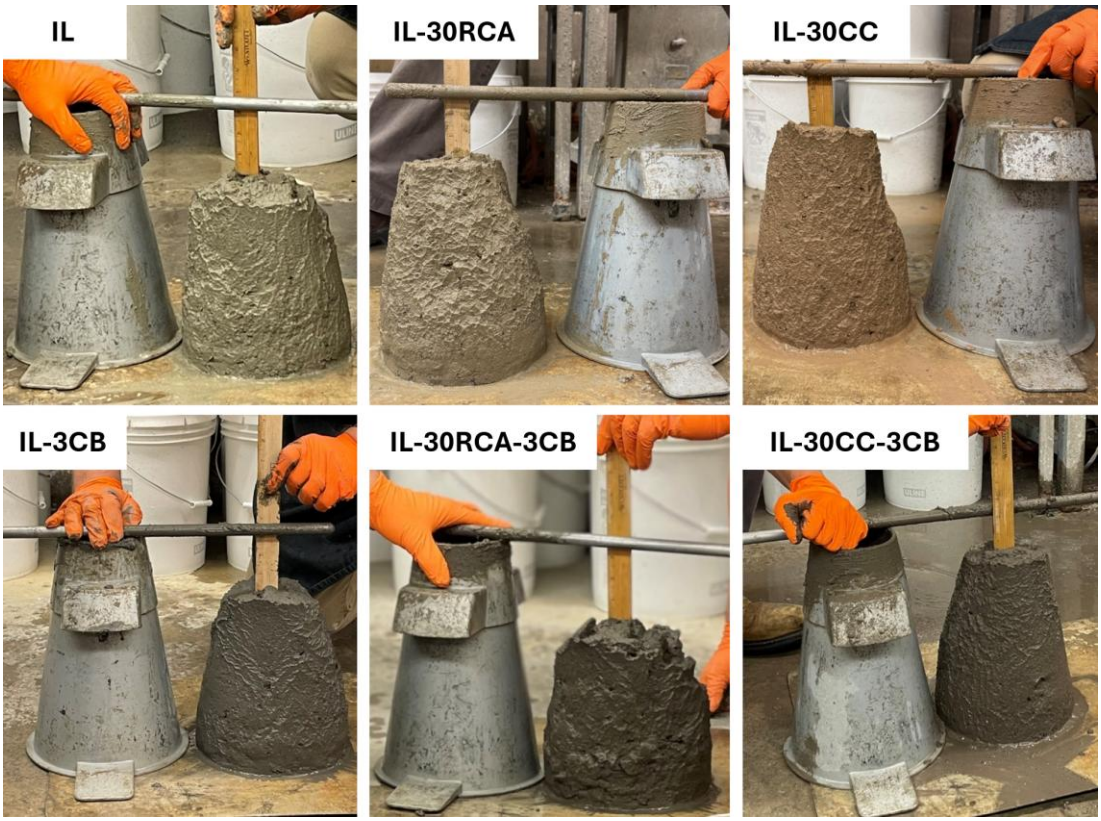



**Figure 7. Consistency of Concrete Mixtures After Slump Test, Immediately Before Proceeding to Molding the Specimens. CB = carbon black; CC = calcined clay; IL = Type IL cement; RCA = reclaimed coal ash (Class F).**

Among the CB-modified mixtures, the mixture incorporating CC required the most reasonable admixture dosages to meet A4 fresh property requirements. This result is attributed to the enhanced air-entraining response CC provides, which helps mitigate the primary challenge associated with CB incorporation. Overall, the results demonstrate that it is feasible to produce mixtures meeting VDOT fresh property requirements with CB; however, the practicality of the elevated admixture dosages may limit its broader implementation.

Even though mixtures containing CB met VDOT air content requirements, adequate freeze-thaw resistance should still be verified through ASTM C666 testing because of the potential for inadequate air void size and distribution (ASTM International, 2026e). In addition, field testing is encouraged to ensure satisfactory performance.

## Concrete Compressive Strength

Figure 8 presents the compressive strength results. The incorporation of CB resulted in a strength reduction ranging from 8 to 23%, depending on the mixture and curing age, corresponding to a small to moderate decrease. The magnitude of this reduction was lowest in the mixture incorporating CC, in which strength decreased by approximately 15% at 7 days and only 8% at 91 days. In contrast, the mixture containing RCA exhibited a larger reduction, with a 21% decrease at 7 days and a 17% decrease at 91 days. For the IL mixture, incorporating CB led to relatively consistent strength reductions of approximately 20 to 23% across all testing ages.

These results indicate that SCMs, particularly CC, provide a synergistic effect that mitigates the strength loss associated with cement dilution from CB incorporation.

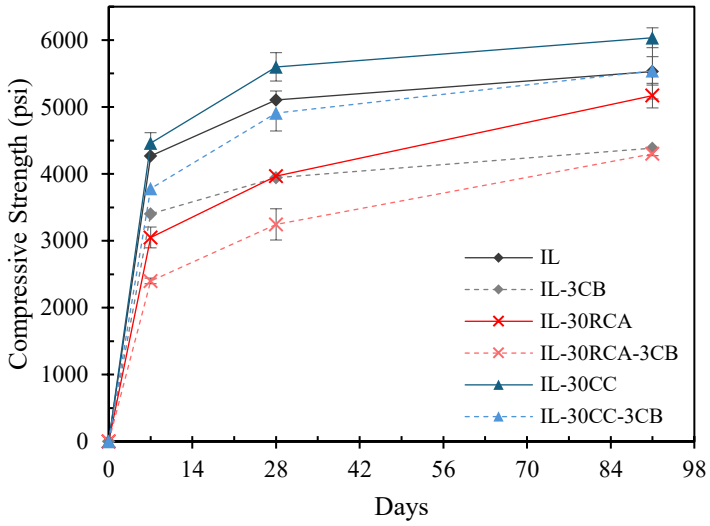



**Figure 8. Compressive Strength of Concrete Mixtures. CB = carbon black; CC = calcined clay; IL = Type IL cement; RCA = reclaimed coal ash (Class F).**

Of the mixtures evaluated, only IL, IL-30CC, and IL-30CC-3CB satisfied the minimum 28-day compressive strength requirement of 4,000 psi for Class A4 concrete as specified by VDOT. However, all mixtures exceeded this requirement at 91 days. This behavior reflects the slower pozzolanic reactivity of RCA (approximately 150 J/g of SCM), which delays strength development, compared with the higher reactivity of CC (greater than 300 J/g of SCM), which promotes more rapid strength gain.

Overall, these findings suggest that when incorporating CB into concrete mixtures with RCA, a reduction in w/cm below 0.45 may be necessary to meet strength requirements. In contrast, incorporating CB in mixtures with CC may not require mixture adjustments to achieve the specified compressive strength.

## Elastic Modulus

Figures 9a and 9b present the elastic modulus and Poisson's ratio of the concrete mixtures, respectively. For the IL and IL-30RCA mixtures, the incorporation of CB reduced the elastic modulus by approximately 4 to 10%. In contrast, for the IL-30CC mixture, CB resulted in a negligible decrease of approximately 2% at 7 days and slight increases at later ages (28–91 days), ranging from 6 to 8%. Overall, the effect of CB on elastic modulus was relatively small.

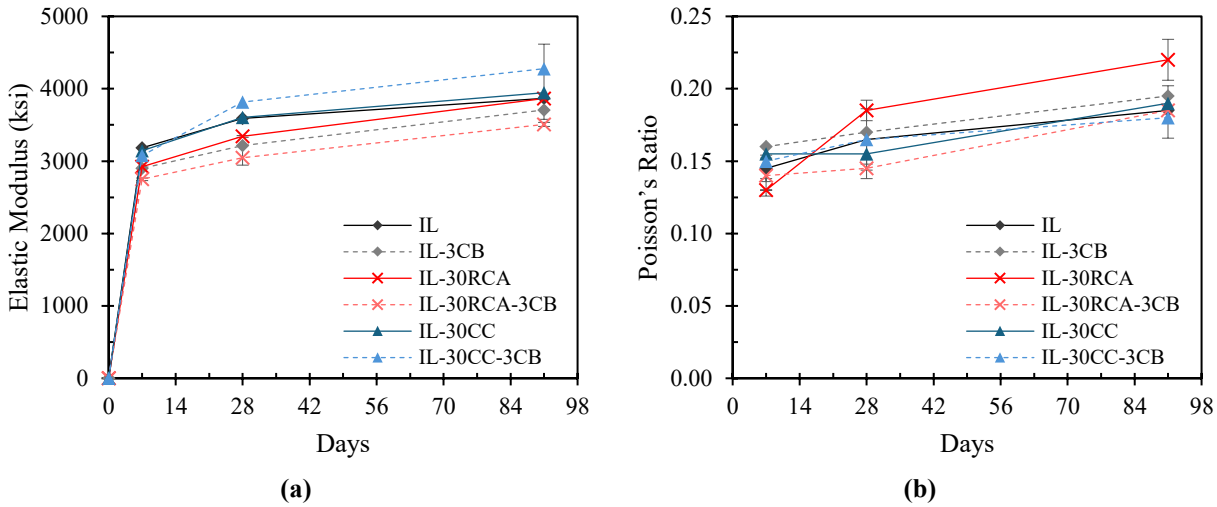



**Figure 9. Concrete Properties: (a) Elastic Modulus; (b) Poisson's Ratio. CB = carbon black; CC = calcined clay; IL = Type IL cement; RCA = reclaimed coal ash (Class F).**

The Poisson's ratio results did not show a consistent trend with CB incorporation. For the IL mixture, CB resulted in increases of approximately 3 to 10%, whereas for the IL-30CC mixture, changes ranged from -3% to 7%. In the case of the IL-30RCA mixture, the effect was more variable, with changes ranging from -22% to 8%, depending on the testing age. Except for IL-30RCA, all mixtures tended to converge to a Poisson's ratio of approximately 0.19 ± 0.01 at 91 days.

Overall, the results indicate that the incorporation of 3% CB does not produce meaningful or concerning changes in the elastic modulus or Poisson's ratio of the evaluated concrete mixtures.

## Surface Resistivity

Figure 10 presents the surface resistivity results. The incorporation of CB reduced the resistivity of the IL and IL-30CC mixtures by approximately 2 to 16%, depending on the testing age, whereas for the IL-30RCA mixture, CB incorporation resulted in a slight increase in resistivity of 0 to 16%. Overall, these results indicate that CB has a relatively small effect on resistivity, with a general tendency toward decreasing resistivity values. Given the electrically based nature of the test, this behavior may be attributed, at least in part, to the conductive nature of CB, which can artificially lower measured resistivity. Therefore, the observed reduction in resistivity may not fully reflect an increase in chloride permeability but rather interference of CB with the measurement method. Notwithstanding, the overall effect of CB on resistivity was limited. It is important to note, however, that at higher dosages than those evaluated here (i.e., 3% cement replacement by mass), this interference may be amplified, warranting further investigation.

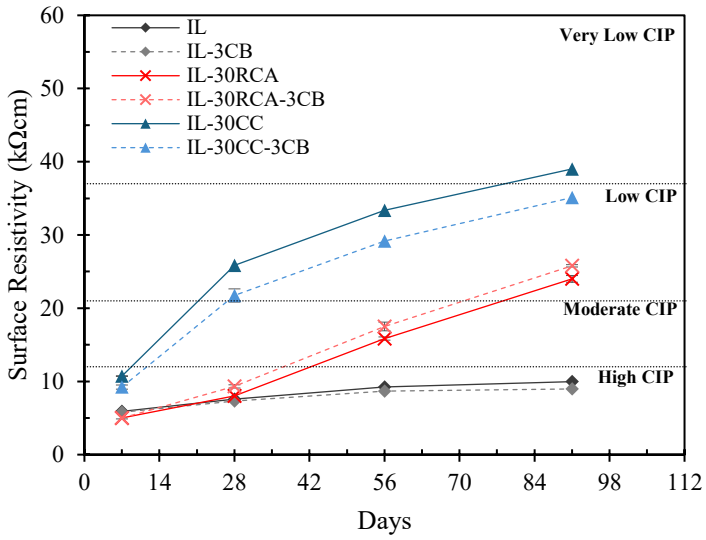



**Figure 10. Surface Resistivity of Concrete Mixtures. CB = carbon black; CC = calcined clay; CIP = chloride ion penetrability; IL = Type IL cement; RCA = reclaimed coal ash (Class F).**

In general, the mixtures without SCMs (i.e., IL and IL-3CB) remained within the high chloride ion penetrability category, which is unfavorable for long-term durability. In contrast, mixtures incorporating RCA or CC, with or without CB, fell within the low to very low chloride ion penetrability categories, highlighting the significant role of SCMs in reducing concrete permeability and improving durability.

## Chloride Permeability

Figure 11 presents rapid chloride permeability test results for specimens subjected to accelerated curing in accordance with ASTM C1202 (ASTM International, 2025c). For the control IL mixture, the incorporation of CB resulted in a 39% increase in permeability, indicating either a detrimental effect of CB on permeability or interference with the test method, consistent with observations from the surface resistivity results. In contrast, when CB was incorporated into mixtures containing RCA or CC, only negligible changes in permeability were observed, suggesting a synergistic interaction between CB and SCMs.

For mixtures without SCMs (i.e., IL and IL-3CB), the VDOT requirement for Class A4 concrete of less than 2,500 Coulombs was not met, with the IL and IL-3CB mixtures falling within the moderate and low chloride ion penetrability categories, respectively. In contrast, all mixtures incorporating RCA or CC, with or without CB, satisfied the requirement, exhibiting permeability values below 1,000 Coulombs, corresponding to very low chloride ion penetrability.

These results highlight the critical role of SCMs in reducing concrete permeability and enhancing durability. Furthermore, they support VDOT specifications that mandate the use of SCMs in concrete mixtures.

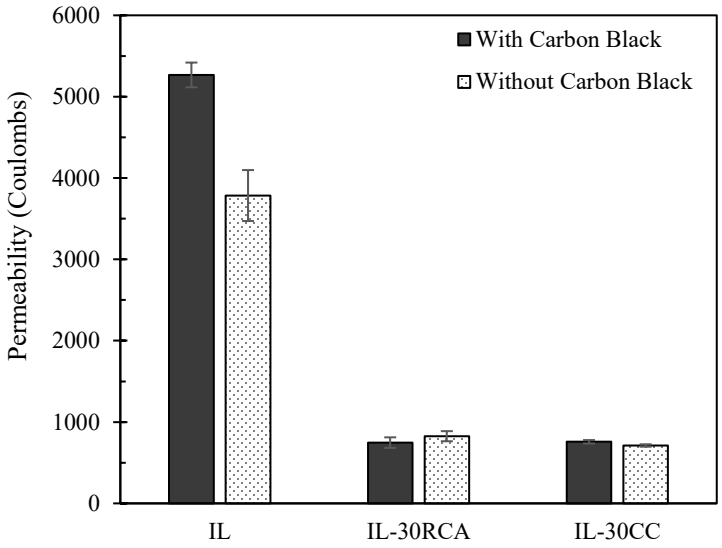



**Figure 11. Concrete Permeability After 28 Days (Accelerated Curing). CC = calcined clay; IL = Type IL cement; RCA = reclaimed coal ash (Class F).**

## Chloride Migration Coefficient

Figure 12 presents the non-steady-state chloride migration coefficients obtained from the chloride migration tests. Testing was conducted only for the mixtures containing CB (i.e., IL-3CB, IL-30RCA-3CB, and IL-30CC-3CB) after 196 ± 7 days of curing. To evaluate the effect of CB on the chloride migration coefficient, data from a previous Virginia Transportation Research Council (VTRC) project were used as controls (Arce et al., 2026). In that study, equivalent mixtures to IL, IL-30RCA, and IL-30CC were tested under the same chloride migration protocol at 196 days of curing. Because the same materials, admixtures, and laboratory facilities were used to produce and test the specimens in both studies, the previously obtained data provide a reasonably consistent benchmark for comparison.

As Figure 12 shows, the effect of CB on the IL mixture was negligible, resulting in less than a 2% reduction in the chloride migration coefficient. In contrast, the IL-30RCA mixture exhibited a 37% decrease in the migration coefficient with the incorporation of CB, whereas the IL-30CC mixture showed a 52% increase when CB was added. However, a two-tailed t-test assuming equal variances indicated that the difference between IL-30CC and IL-30CC-3CB was not statistically significant (p-value = 0.086), given the variability of the test results. On the other hand, the decrease observed for IL-30RCA-3CB relative to IL-30RCA was statistically significant (p-value = 0.029). Overall, at the dosage evaluated, CB does not appear to produce a meaningful detrimental effect on the ability of concrete to resist chloride penetration.

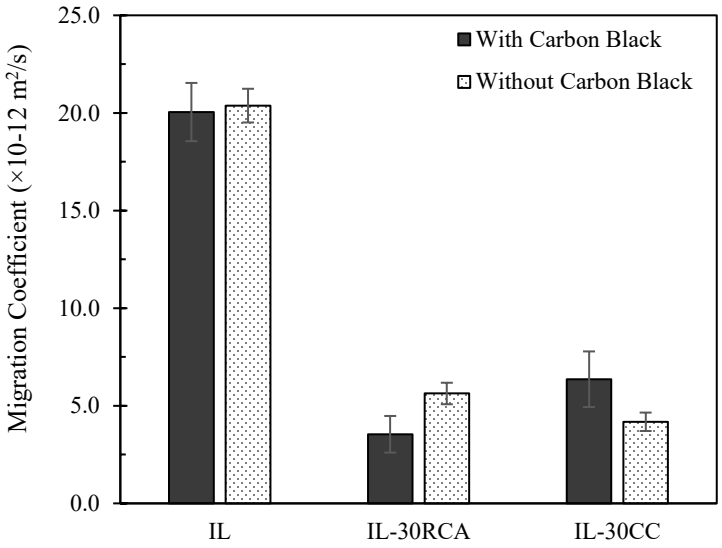



**Figure 12. Non-Steady-State Chloride Migration Coefficient of Concrete. Data for Mixtures Without Carbon Black Were Obtained from VTRC 26-R52 (Arce et al., 2026). CC = calcined clay; IL = Type IL cement; RCA = reclaimed coal ash (Class F).**

## Drying Shrinkage

Figure 13 presents the drying shrinkage results. At 28 days, mixtures without CB exhibited shrinkage values ranging from 411 to 509 με, whereas mixtures incorporating CB ranged from 464 to 608 με. For reference, the maximum allowable 28-day drying shrinkage for Low Shrinkage Class A4 modified concrete is 350 με according to VDOT's (2020) *Road and Bridge Specifications*. The higher shrinkage values observed in this study were expected because the mixtures correspond to Class A4 General concrete, which uses a higher cementitious content (635 lb/yd$^3$) compared with the 600 lb/yd$^3$ limit specified for Low Shrinkage Class A4 concrete. Consequently, the measured shrinkage values are consistent with the higher cementitious content.

Mixtures incorporating CB generally exhibited higher shrinkage. At 28 days, increases ranged from 4 to 31%, and at 91 days, increases ranged from 4 to 26%. It was also observed that mixtures containing RCA or CC tended to reduce shrinkage. Even with CB incorporated, mixtures with RCA or CC produced shrinkage values similar to or less than those of the control IL mixture.

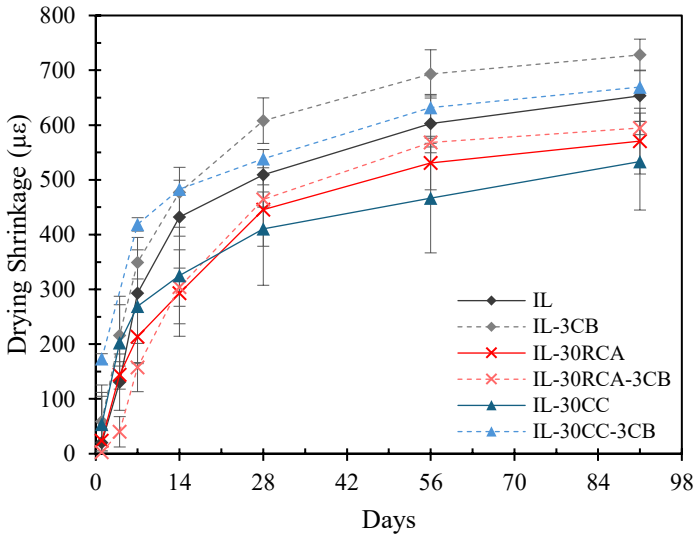



**Figure 13. Concrete Drying Shrinkage. CB = carbon black; CC = calcined clay; IL = Type IL cement; RCA = reclaimed coal ash (Class F).**

## Summary of Findings

### Characterization

- CB consists of more than 86% carbon and is composed of fine particles with a narrow size distribution, having median particle sizes of 15.6 µm (as received) and 2.5 µm (processed). Its micro-morphology is complex, characterized by dense networks of agglomerated irregular or fiber-like structures. According to the ASTM C1897 SCM reactivity test (ASTM International, 2020), CB exhibits a 7-day cumulative heat of hydration below 100 J/g of SCM, which is indicative of largely inert materials. Accordingly, CB primarily functions as a filler material in concrete rather than as a reactive SCM.

### Evaluation of the Concrete Properties

- CB substantially increases the demand for water-reducing and air-entraining admixtures needed to achieve VDOT fresh-property requirements for Class A4 General concrete. Mixtures containing CB required approximately 1.5 to 2 times more HRWR and 20 to 45 times more AEA to meet target slump and air contents. As a result, entraining air in CB-modified mixtures presents a significant practical challenge because the required AEA dosages typically exceed common practice ranges. However, the CB-modified mixture incorporating CC (IL-30CC-3CB) required considerably less AEA to reach the target air content, suggesting that this mixture may be a more practical option.
- Incorporating CB reduced compressive strength across all mixtures by 8 to 23%, with the magnitude of reduction depending on mixture type and curing age. Mixtures containing SCMs showed smaller strength losses, and these losses diminished at later ages. CC was most effective in mitigating strength reductions, with only an 8% decrease reported at 91 days. Although only IL, IL-30CC, and IL-30CC-3CB met the 28-day VDOT requirement

of 4,000 psi for Class A4 General concrete, all mixtures exceeded this requirement by 91 days. These results suggest that mixtures containing RCA may require a lower w/cm to meet strength targets when incorporating CB, whereas CB may be used with CC without requiring mixture adjustments.

- The incorporation of CB had a minimal effect on the elastic modulus and Poisson's ratio of the evaluated concrete mixtures. Elastic modulus reductions were small across all mixtures, with CC-containing mixtures showing negligible decreases at early ages and slight increases at later ages. Poisson's ratio exhibited no consistent trend with CB addition, although most mixtures converged to approximately $0.19 \pm 0.01$ by 91 days. Overall, the findings indicate that CB at the dosage used does not produce meaningful or concerning changes in the elastic or deformation-related behavior of the concrete mixtures studied.
- The incorporation of CB generally resulted in slight increases in chloride permeability as measured through surface resistivity and rapid chloride permeability testing. The only exception was the mixture containing RCA (IL-30RCA-3CB), which showed no change to a small reduction in chloride permeability. Nevertheless, all mixtures incorporating CC or RCA, regardless of CB inclusion, comfortably met VDOT permeability requirements for Class A4 General concrete, exhibiting values below 1,000 Coulombs. In contrast, mixtures without CC or RCA did not meet VDOT limits and instead fell within the moderate- to high-chloride ion penetrability categories. Overall, the results demonstrate that mixtures containing CB can still meet VDOT permeability requirements and produce concretes with low chloride ion penetrability. The chloride migration test results also support this outcome, suggesting that, at the dosage evaluated, CB does not meaningfully impair the concrete's resistance to chloride penetration. The increases in chloride permeability inferred from the surface resistivity and rapid chloride permeability tests may therefore partly reflect the conductive nature of CB and its potential to interfere with electrically based test methods, rather than a true increase in permeability.
- The incorporation of CB generally increased shrinkage at both 28 and 91 days, with increases ranging from 4 to 31%. However, the presence of SCMs mitigated shrinkage increases because mixtures containing RCA or CC demonstrated similar or lower shrinkage than the control IL mixture, even when CB was included. These findings highlight that although CB may slightly elevate drying shrinkage, the use of SCMs effectively counterbalances this effect.

## CONCLUSIONS

- *CB primarily functions as a filler material in concrete*. CB is composed almost entirely of carbon, consists of fine particles with a complex micro-morphology characterized by dense networks of agglomerated irregular or fiber-like structures, and does not demonstrate the reactivity levels (per ASTM C1897) typically associated with SCMs.

- *Concrete mixtures meeting VDOT Class A4 General concrete fresh and hardened property requirements can be produced with CB*. However, achieving adequate workability and air content requires substantially higher admixture dosages, especially air-entraining admixture

because CB dramatically reduces its effectiveness. This conclusion applies to the 3% cement replacement level (by mass) evaluated in this study.

- *Within the scope and dosage evaluated in this study, incorporating CB does not provide performance benefits to concrete beyond the potential environmental advantage of a reduced GWP*. Importantly, the magnitude of GWP reduction depends heavily on the specific source of the CB, and achieving a genuinely carbon-negative CB, although theoretically possible, may be challenging in practice. However, CB can impart added functionalities relevant to transportation infrastructure—most notably de-icing (self-heating) and structural monitoring (self-sensing) capabilities—but realizing these functions generally requires higher dosages than those evaluated and was beyond the scope of this study.

## RECOMMENDATIONS

1. *VDOT should not pursue the use of CB in concrete mixtures at this time.*

2. *VTRC should continue to monitor the emergence and industry relevance of novel carbon-based concrete additives—including CB, biochar, graphene, and others—that may offer performance enhancements, environmental benefits, or added functionalities for VDOT concretes.*

## IMPLEMENTATION AND BENEFITS

The researcher 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 Recommendations 1 and 2, VDOT's Materials Division will not pursue the approval of CB for use in VDOT's concrete. VTRC will continue to monitor the emergence and industry relevance of novel carbon-based additives for concrete.*

### Benefits

Benefits of this study include keeping VDOT informed about the emergence of new carbon-based additives, which may play an increasingly important role in the future of concrete technology. The knowledge generated on the CB performance in concrete equips VDOT to critically evaluate emerging carbon-based additive products, ensuring the agency is prepared to assess and implement new materials as they enter the market.

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## REFERENCES

American Association of State Highway and Transportation Officials. *AASHTO T358: Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration*. Washington, DC, 2023.

Arce, G., Jiang, Z., Behravan, A., Colosi Peterson, L., and Ozbulut, O. *Addressing Fly Ash Shortage with Limestone Calcined Clay Cement*. VTRC 26-R52. Virginia Transportation Research Council, Charlottesville, VA, 2026.

ASTM International. *ASTM C1897-20: Standard Test Methods for Measuring the Reactivity of Supplementary Cementitious Materials by Isothermal Calorimetry and Bound Water Measurements*. West Conshohocken, PA, 2020.

ASTM International. *ASTM C511-21: Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes*. West Conshohocken, PA, 2021.

ASTM International. *ASTM C469/C469M-22: Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*. West Conshohocken, PA, 2022.

ASTM International. *ASTM C33/C33M-24a: Standard Specification for Concrete Aggregates*. West Conshohocken, PA, 2024a.

ASTM International. *ASTM C138/C138M-24a: Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete*. West Conshohocken, PA, 2024b.

ASTM International. *ASTM C157/C157M-24e1: Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete*. West Conshohocken, PA, 2024c.

ASTM International. *ASTM C595/C595M-25: Standard Specification for Blended Hydraulic Cements*. West Conshohocken, PA, 2025a.

ASTM International. *ASTM C618-25a: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*. West Conshohocken, PA, 2025b.

ASTM International. *ASTM C1202-25: Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*. West Conshohocken, PA, 2025c.

ASTM International. *ASTM C192/C192M-26: Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*. West Conshohocken, PA, 2026a.

ASTM International. *ASTM C143/C143M-26a: Standard Test Method for Slump of Hydraulic-Cement Concrete*. West Conshohocken, PA, 2026b.

ASTM International. *ASTM C231/C231M-26: Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method*. West Conshohocken, PA, 2026c.

ASTM International. *ASTM C39/C39M-26: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. West Conshohocken, PA, 2026d.

ASTM International. *ASTM C666/C666M-26: Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*. West Conshohocken, PA, 2026e.

Barbhuiya, S., Nepal, J., and Das, B.B. Properties, Compatibility, Environmental Benefits and Future Directions of Limestone Calcined Clay Cement (LC3) Concrete: A Review. *Journal of Building Engineering*, Vol. 79, 2023.

Berke, N.S., Inceefe, A.N., Kramer, A., and Antommattei, O.R. Durability of Portland Limestone Cement Concrete. *Concrete International*, Vol. 44, No. 1, 2022, pp. 34–39.

Chanut, N., Stefaniuk, D., Weaver, J.C., Zhu, Y., Shao-Horn, Y., Masic, A., and Ulm, F.-J. Carbon-Cement Supercapacitors as a Scalable Bulk Energy Storage Solution. *Proceedings of the National Academy of Sciences*, Vol. 120, No. 32, 2023.

Diaz-Loya, I., Juenger, M., Seraj, S., and Minkara, R. Extending Supplementary Cementitious Material Resources: Reclaimed and Remediated Fly Ash and Natural Pozzolans. *Cement and Concrete Composites*, Vol. 101, 2019, pp. 44–51.

Dinesh, A., Saravanakumar, P., Rahul Prasad, B., and Kilbert Raj, S. Carbon Black Based Self-Sensing Cement Composite for Structural Health Monitoring: A Review on Strength and Conductive Characteristics. *Materials Today: Proceedings*, 2023.

Gupta, S., Kua, H.W., and Low, C.Y. Use of Biochar as Carbon Sequestering Additive in Cement Mortar. *Cement and Concrete Composites*, Vol. 87, 2018, pp. 110–129.

Gwon, S., Kim, H., and Shin, M. Self-Heating Characteristics of Electrically Conductive Cement Composites with Carbon Black and Carbon Fiber. *Cement and Concrete Composites*, Vol. 137, 2023.

Hamidi, F., and Tunstall, L.E. Insights into the Influence of Biochar Powder on the Fresh State Properties and Strength Development of Concrete. *Construction and Building Materials*, Vol. 498, 2025.

Kalt, G., Thunshirn, P., Krausmann, F., and Haberl, H. Material Requirements of Global Electricity Sector Pathways to 2050 and Associated Greenhouse Gas Emissions. *Journal of Cleaner Production*, Vol. 358, 2022.

Kanagaraj, B., Anand, N., Samuvel Raj, R., and Lubloy, E. Techno-Socio-Economic Aspects of Portland Cement, Geopolymer, and Limestone Calcined Clay Cement (LC3) Composite Systems: A State-of-Art-Review. *Construction and Building Materials*, Vol. 398, 2023.

Klyuev, S., Ayubov, N., Ageeva, M., Fomina, E., Klyuev, A., Usanova, K., and Shorstova, E. Fine-Grained Concrete Properties in Depending on Carbon Black Additive Introducing Methods. *Journal of Materials Research and Technology*, Vol. 32, 2024, pp. 1996–2004.

Krishnan, S., Emmanuel, A.C., Shah, V., Parashar, A., Mishra, G., Maity, S., and Bishnoi, S. Industrial Production of Limestone Calcined Clay Cement: Experience and Insights. *Green Materials*, Vol. 7, No. 1, 2018, pp. 15–27.

Londoño-Zuluaga, D., Gholizadeh-Vayghan, A., Winnefeld, F., Avet, F. Haha, M.B., Bernal, S.A., Cizer, Ö., Cyr, M., Dolenec, S., Durdzinski, P., Haufe, J., Hooton, D., Kamali-Bernard, S., Li, X., Marsh, A.T.M., Marroccoli, M., Mrak, M., Muy, Y., Patapy, C., Pedersen, M., Sabio, S., Schulze, S., Snellings, R., Telesca, A., Vollpracht, A., Ye, G., Zhang, S., and Scrivener, K. Report of RILEM TC 267-TRM Phase 3: Validation of the R3 Reactivity Test Across a Wide Range of Materials. *Materials and Structures*, Vol. 55, No. 5, 2022.

Mensah, R.A., Wang, D., Shanmugam, V., Sas, G., Försth, M., and Das, O. Fire Behaviour of Biochar-Based Cementitious Composites. *Composites Part C: Open Access*, Vol. 14, 2024.

Monteiro, A.O., Cachim, P.B., and Costa, P.M.F.J. Self-Sensing Piezoresistive Cement Composite Loaded with Carbon Black Particles. *Cement and Concrete Composites*, Vol. 81, 2017, pp. 59–65.

Noyes, G. *Development of a Carbon Formation Reactor for Carbon Dioxide Reduction*. NASA-CR-171907. National Aeronautics and Space Administration, Washington, DC, 1985.

NT Build 492. *Concrete, Mortar and Cement-Based Repair Materials: Chloride Migration Coefficient from Non-Steady-State Migration Experiments*. Nordtest, Espoo, Finland, 1999.

Portland Cement Association. *Environmental Product Declaration: Portland-Limestone Cement*. EPD No. 196, Program Operator: ASTM International, Revised October 2023. https://www.cement.org/wp-content/uploads/2024/07/pca_epd_plc_athena_final_revised_nov2023.pdf. Accessed July 2026.

Rosner, F., Bhagde, T., Slaughter, D.S., Zorba, V., and Stokes-Draut, J. Techno-Economic and Carbon Dioxide Emission Assessment of Carbon Black Production. *Journal of Cleaner Production*, Vol. 436, 2024.

Scrivener, K., Martirena, F., Bishnoi, S., and Maity, S. Calcined Clay Limestone Cements (LC3). *Cement and Concrete Research*, Vol. 114, 2018, pp. 49–56.

Sirico, A., Bernardi, P., Sciancalepore, C., Vecchi, F., Malcevschi, A., Belletti, B., and Milanese, D. Biochar from Wood Waste as Additive for Structural Concrete. *Construction and Building Materials*, Vol. 303, 2021.

Solid Carbon Products. The Noyes Process: Turning Waste $CO_2$ into Profitable Carbon Products, 2022. https://www.solidcarbonproducts.com/. Accessed June 25, 2026.

Soliman, N.A., Chanut, N., Deman, V., Lallas, Z., and Ulm, F.-J. Electric Energy Dissipation and Electric Tortuosity in Electron Conductive Cement-Based Materials. *Physical Review Materials*, Vol. 4, 2020.

Stefaniuk, D., Krakowiak, K.J., Świtała, M., Bebłacz, D., and Prybylski, P. Electron-Conductive Concrete as a Self-Deicing System. *Materiały Budowlane*, Vol. 638, No. 10, 2025.

Subedi, S., Arce, G.A., Hassan, M.M., Huang, O., Radovic, M., and Hossain, Z. Evaluation of Alternative Sources of Supplementary Cementitious Materials for Concrete Materials. *Transportation Research Record*, Vol. 2676, No. 6, 2022, pp. 287–301.

Virginia Department of Transportation. *Road and Bridge Specifications*. Richmond, VA, 2020.

Wang, H., Li, C., Gao, H., Zhao, Y., Xia, H., Zhou, C., Zhong, S., and Zhao, Q. Improvement of Dispersants on Nano Carbon Black-Modified Cement Paste: Performance, Microstructure and Carbon Footprint. *Frontiers in Materials*, Vol. 11, 2024.

Wu, J., Xie, S., Ji, Z., Wu, Z., Ma, C., and Wang, J. Effect of Carbon Black Dispersion on Cement Mortar Properties: Microstructure and Electromagnetic Properties. *Mechanics of Advanced Materials and Structures*, Vol. 32, No. 17, 2025, pp. 4244–4259.

Zhang, Q., Luan, C., Yu, C., Huang, Y., and Zhou, Z. Mechanisms of Carbon Black in Multifunctional Cement Matrix: Hydration and Microstructure Perspectives. *Construction and Building Materials*, Vol. 346, 2022.