TECH**NOTE**

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Validity of Electrical-Based Durability Tests for Concrete Containing Colloidal Nanosilica

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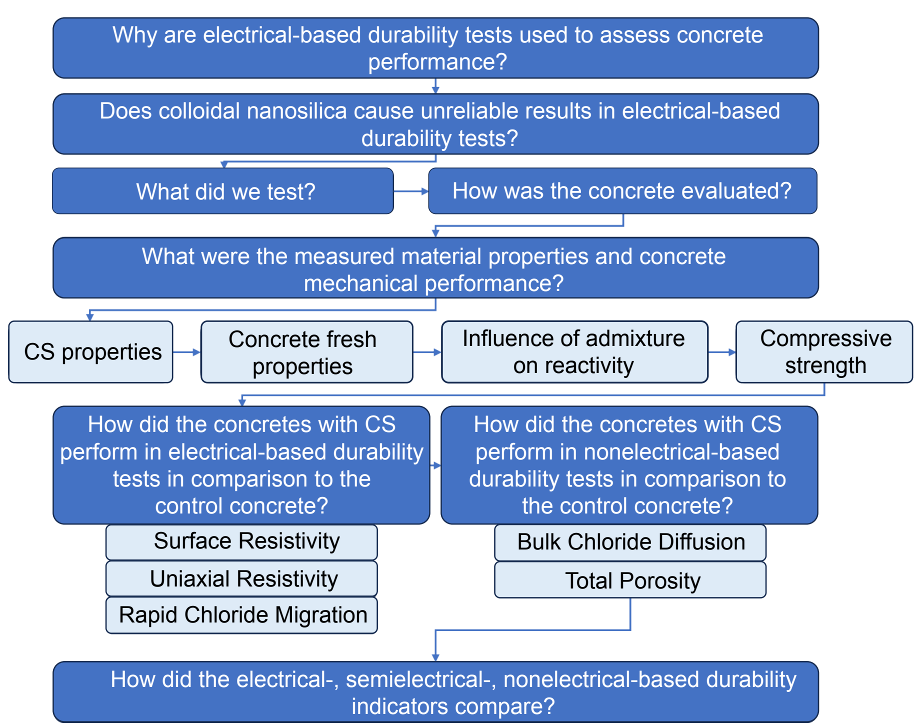
FHWA Contact: Michelle A. Cooper, (ORCID: 0000-0001-8112-693X), HRDI-10, michelle.cooper@dot.gov

Authors:
Amir Malakooti, GENEX Systems, (ORCID: 0000-0001-8177-3571), amir.malakooti.ctr@dot.gov
Payam Hosseini, GENEX Systems, (ORCID: 0000-0001-5670-577X), payam.hosseini.ctr@dot.gov
Michelle A. Cooper, FHWA, (ORCID: 0000-0001-8112-693X), michelle.cooper@dot.gov
Scott Muzenski, GENEX Systems, (ORCID: 0000-0003-1694-0278), scott.muzenski.ctr@dot.gov

INTRODUCTION

The purpose of this study is to answer the question of whether the results of electrical-based durability tests appropriately indicate long-term performance of concretes made with admixtures containing colloidal nanosilica (CS). The structure of this document is presented in figure 1.

Figure 1. Chart. Graphical abstract describing the structure of the technote.



Source: FHWA.

WHY ARE ELECTRICAL-BASED DURABILITY TESTS USED TO ASSESS CONCRETE PERFORMANCE?

Concrete durability degradation mechanisms, such as reinforcement corrosion, chemical attacks, salt scaling, and freeze-thaw damage, typically relate to concrete pore volume, pore connectivity, and pore solution characteristics. These parameters are known as concrete transport properties. Hydration and pozzolanic reactions densify the cementitious system and reduce fluid and ion transport as concrete ages (with most of the reactions occurring between initial contact with water and 120 d of age, but most rapidly up to 56 d), consequently improving concrete durability. Therefore, quality assurance testing is performed within this 0 to 56-d age timeframe. Concrete durability tests can be subdivided into three methodology-related categories, including electrical , semielectrical-, and nonelectrical-based durability tests. Electrical-based concrete durability tests—such as surface resistivity (American Association of State Highway and Transportation Officials (AASHTO) T 358) and uniaxial resistivity (AASHTO T 402))—involve passing an electrical potential and measuring the resistance across a distance estimated based on the specimen and sensor geometries.[1,2] Electricity travels through the path of least resistance, and therefore typically transmits through concrete via the pore network.[1,2] Electricity moves through concrete faster when the pores are larger with higher fluid volume, are more connected, and have higher ionic content (e.g., more salts and alkalis in the pore solution), resulting in lower resistivity. Therefore, these tests measure concrete transport properties.[1–3] Higher concrete resistivity measurements from these tests indicate reduced ionic and fluidic transport and suggest improved long-term concrete durability.

Semielectrical tests include rapid chloride migration (NT Build 492 and AASHTO T 357), a non-steady-state electromigration test that utilizes electrical current and chemical concentration gradients to accelerate salt penetration and migration through the concrete pore structure.[4,5] However, these tests use electrical boundary conditions (applied voltage), so the presence of conductive inclusions has potential to increase chloride migration. Conductivity is the inverse of resistivity, and therefore a concrete constituent with a higher conductivity than the other constituents may influence the measured resistivity of a concrete mixture. Following the penetration and migration of chlorides into concrete, NT Build 492 specifies performing physical measurements of chloride penetration depths to then calculate the non-steady-state chloride migration coefficient.[4] Higher chloride migration coefficients directly indicate higher potential chloride penetration and therefore lower durability.

Nonelectrical durability tests, such as bulk chloride diffusion (ASTM International® (ASTM) C1556), can be performed to measure the chloride concentration across a concrete depth profile when exposed to a chloride-concentrated solution.[6] No electrical acceleration is involved. The chloride profiles are then used to calculate apparent chloride diffusion coefficients to assess durability and potentially be used in service life modeling. A higher chloride diffusion coefficient indicates a greater concentration of chloride ions penetrate farther into the concrete. As a result, higher chloride diffusion coefficients indicate a shorter amount of time to corrosion initiation of steel reinforcement and dowels, and greater ease of ionic and fluidic transport that may contribute to other deterioration mechanisms.

Electrical-based durability tests have gained popularity as a research, mixture design, and mixture acceptance tool due to their fast, reliable, and nondestructive nature as an alternative to traditional concrete durability tests such as ASTM C1556.[3,6] In recent years, the Federal Highway Administration (FHWA) and the concrete industry have evaluated and demonstrated the benefits of using electrical-based tests for mixture qualifications, quality control, and quality assurance of concrete.[7–9]

DOES CS CAUSE UNRELIABLE RESULTS IN ELECTRICAL-BASED DURABILITY TESTS?

Silicon dioxide (SiO_2) nanoparticles (also known as nanosilica) are the most reactive supplementary cementitious materials (SCMs) that can be used in a cementitious system.[10–12] Nanosilica is a pure form of SiO_2 with the same active chemistry as silica fume and with nanosized spherical particles. Depending on its specific surface area, the application of low dosages of nanosilica (less than 10 percent by weight of cementitious content) can enhance the mechanical and durability properties of concrete materials.[10,12,13] Nanosilica exhibits rapid pozzolanic reactivity due to its quick dissolution in high-pH environments, offers a large surface area to promote calcium-silicate-hydrate (C-S-H) formation, and fills very fine pores in the matrix.[10–12] Nanosilica is most commonly used in suspension (hydrosol) form because it is easier to mix, improves the dispersion of SiO_2 nanoparticles in concrete mixtures, and minimizes health risks associated with exposure to fine dust.[14,15] Therefore, CS is a monodispersed solution of SiO_2 nanoparticles.[10,15]

During the National Concrete Consortium meeting in Spring 2022, and at other industry meetings since, attendees raised the question—though no data were found—whether commercially available CS products used in the concrete industry are conductive and may decrease concrete electrical resistivity. This conductivity could decrease resistivity even when the concrete matrix maintains adequate durability, potentially making electrical-based durability tests unreliable. The presence of conductive materials within concrete, such as high dosages of conductive fibers, can create paths for the electrical current to pass through conductive fibers instead of the concrete matrix, which results in a decrease in concrete resistivity measurements.[16] If conductive inclusions are incorporated into a concrete mixture, electrical-based durability test results may indicate a lower material durability even if the cementitious matrix is dense with a discontinuous pore structure. Electrical-based tests should be used with caution and should be verified against nonelectrical-based durability tests when incorporating conductive materials. Therefore, the purpose of this study is to verify whether electrical-based concrete durability tests can be used for quality assurance of concrete containing commercially available CS admixture products.

WHAT WAS TESTED?

Two concrete mixture types with two water-to-cementitious materials ratios (w/cm) of 0.42 (M1) and 0.47 (M2) were developed to investigate the influence of CS. M1 represents a pavement mixture with a 25-percent paste content (by volume) and a target slump of 2±1 inches. Conversely, M2 represents a bridge deck mixture with a 30-percent paste content (by volume) and a 6±1-inch target slump. Note that a 0.47 w/cm is not typical of concrete transportation infrastructure, but is used for some concrete mixtures containing CS to improve dispersion of CS products and maintain workability and represents the higher range of w/cm used in concretes containing CS.[17] The control concrete mixture designs (M1 and M2) for the study are shown in table 1. Figure 2 illustrates the similarities and differences between the M1 and M2 mixture categories. This study used type IL(10) cement (portland limestone cement with approximately 10 percent limestone content, written in notation specified by ASTM C595[18]) with no additional SCMs to represent the current state of the U.S. cement industry while isolating the effects of CS on concrete performance.

Three commercially available CS admixtures were explored for this study (CS-1, CS-2, and CS-3). Specific gravity, solid content, and conductivity were measured for CS admixtures, and the results are shown in table 2.[19] Two 300-g samples of each commercially available CS admixture were oven-dried at 220 ºF (104 ºC) for 24 h, and the weight loss was used to calculate solid content. The measured average water content and specific gravity from each CS admixture was used to balance the water content in the concrete mixtures cast in the laboratory. A conductivity probe was used to measure admixture conductivity on two 300-g samples of each CS admixture. Table 2 shows that none of the CS admixtures were conductive relative to typical concrete pore solution and other admixture types used in concrete. Typical alkali pore solution conductivity, according to AASHTO T 402, is approximately 92,700 µS/cm (0.01 kΩ-cm) at 73 ºF (23 ºC), which is much more conductive than the tested admixtures.[2]

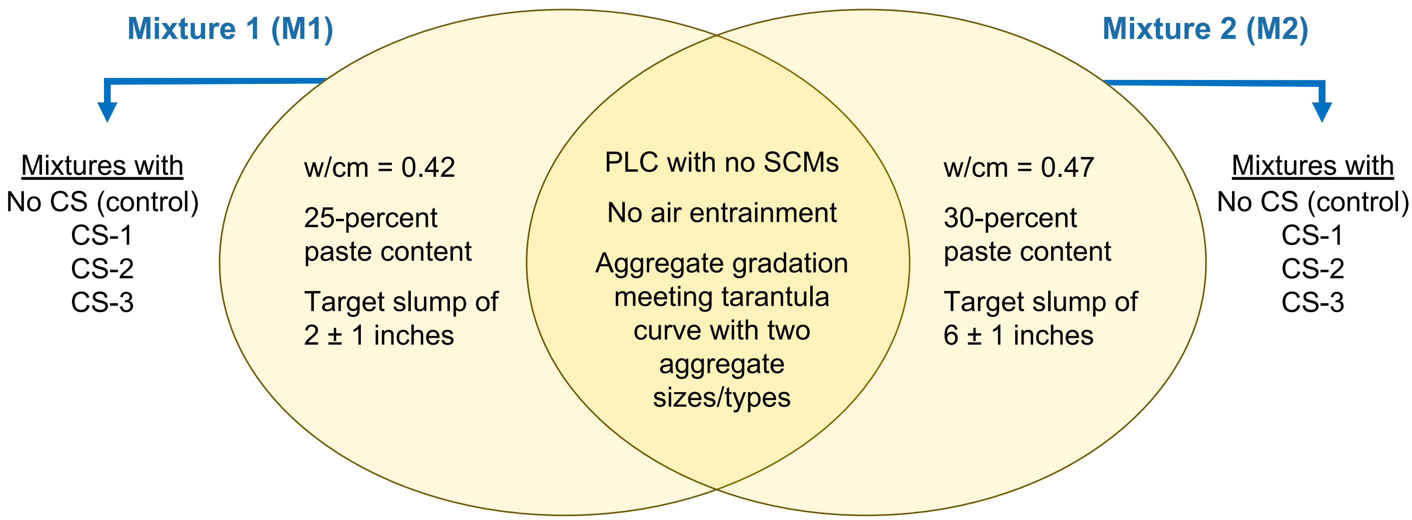
The maximum manufacturer-recommended dosage was used for each commercial CS admixture and incorporated into the M1 and M2 mixtures (table 1) to evaluate the effect of CS on electrical-based durability test results. The target slumps were achieved by optimizing the aggregate gradation using the tarantula curve limits (both mixtures met the pavement and structural tarantula curve limits) and using a polycarboxylate-based, high-range water reducer (HRWR).[20] No other admixtures, such as air entrainer, were included in the concrete mixtures to facilitate isolation of the effects of CS on concrete performance. Each CS admixture was incorporated into the concrete mixing process as directed by each respective manufacturer.

Table 1. Control concrete mixture designs for the study.

Mixture	Coarse Aggregate (lbs/yd^3)	Fine Aggregate (lbs/yd^3)	Cement (lbs/yd^3)	Water (lbs/yd^3)	HRWR (fl oz/cwt*)
M1 Control	1,725	1,677	571	240	6.0
M2 Control	1,725	1,460	642	302	2.2

*Fluid ounces per 100 lbs of cement.

Figure 2. Diagram. Mixture design parameters.



Source: FHWA.
PLC = portland limestone cement.

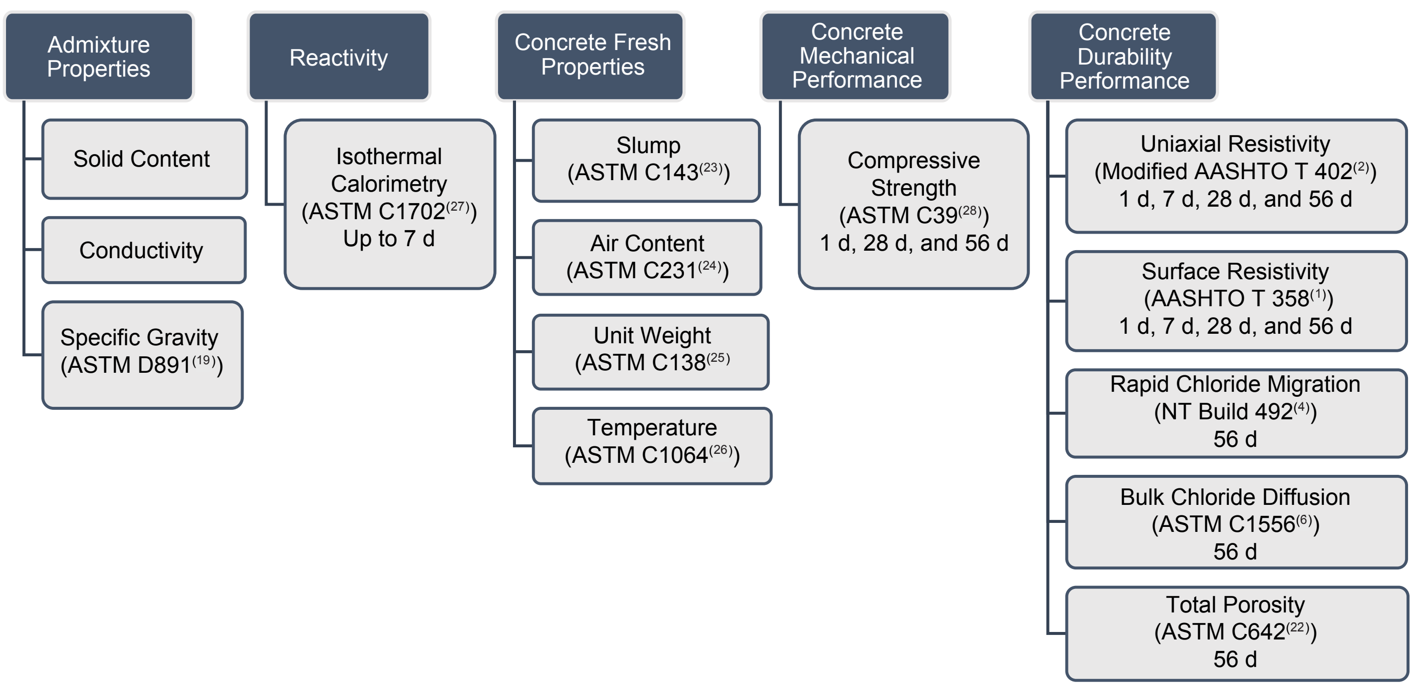
Table 2. CS material properties, with the bolded values indicating the dosages used in this study for each CS.

Admixture Identifier	Average Specific Gravity	Average Solid Content (Percent)	Average Materials Conductivity at 73 °F (µS/cm)	Manufacturer-Recommended CS Dosage	Manufacturer Dosage per Cementitious Weight (Percent)
CS-1	1.15	48.2	3,860	8–**20** fl oz per 100 lbs of cementitious	0.6–**1.5**
CS-2	1.19	53.6	2,580	4–**8** fl oz per 100 lbs of cementitious	0.31–**0.62**
CS-3	1.21	50.0	7,160	0.5–**1.5** percent per cementitious weight	0.5–**1.5**

HOW WAS THE CONCRETE EVALUATED?

Figure 3 depicts the comprehensive test matrix performed during this study, including material properties, admixture reactivity, and fresh and hardened concrete properties. Isothermal calorimetry was performed to characterize the effect of CS on cement hydration during early ages (up to 7 d). Typical fresh concrete properties, including slump, total air content, unit weight, and temperature were measured in accordance with their appropriate standards, as indicated in figure 3. The Box Test was performed in accordance with AASHTO T 396.[21] The Box Test indicates the workability and consolidation of a fresh concrete mixture placed by a slipform paver, and therefore was conducted only on the M1 mixtures which had low w/cm and were intended to represent paving concrete. Concrete samples were demolded 24 h after casting and were moved to a limewater curing tank until testing. Concrete compressive strengths were tested at 1-, 28-, and 56-d ages to provide insights into changes in mechanical performance between the control mixtures (M1 and M2) and mixtures with CS. Concrete durability performance was tested using electrical-based methods of surface and uniaxial resistivity (AASHTO T 358 and AASHTO T 402, respectively), a semielectrical method of rapid chloride migration (NT Build 492), and nonelectrical methods including bulk chloride diffusion (ASTM C1556) and total porosity via vacuum saturation method (ASTM C642 modified to use vacuum saturation at a vacuum pressure of approximately 32 mmHg instead of boil saturation, which is allowed by Note 2 of the standard). (See references 1, 2, 4, 6, and 22.) Uniaxial resistivity was performed using a modified version of AASHTO T 402 because the standard specifies conditioning the concrete in alkali-concentrated solution or in sealed conditions.[2] For this investigation, however, the concretes were conditioned in a limewater bath as specified in AASHTO T 358 for surface resistivity.[1] Limewater tank curing is more typical of mixture qualification quality assurance practices.

Figure 3. Chart. Test matrix summary.



Source: FHWA.

WHAT WERE THE MEASURED MATERIAL PROPERTIES AND CONCRETE MECHANICAL PERFORMANCE?

Concrete Fresh Properties

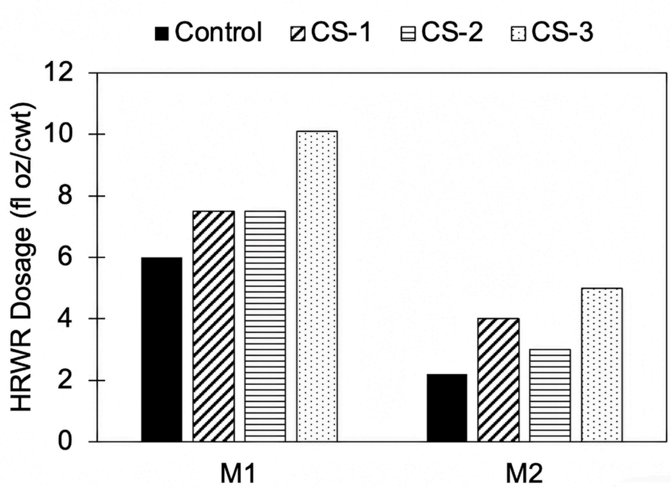
Table 3 displays fresh properties of concrete mixtures produced in this study, including slump, air content, unit weight, and temperature. Table 3 additionally shows the results of the Box Test performed according to AASHTO T 396 for the M1 concrete mixtures, which demonstrated good ratings for slipform paving.[21] HRWR content was modified for each concrete mixture to ensure the same target slump was obtained for the concretes with CS relative to their respective control mixture. The target slump was maintained in this study to minimize the effect of sample preparation on concrete performance. Literature demonstrates that CS has varying effects on concrete workability, which can lead to compaction differences during sample preparation if those variations are not mitigated.[10] Figure 4 shows that mixtures containing CS needed higher dosages of HRWR to achieve the same target slump as the corresponding control mixture. This increase in HRWR dosage was more significant in the mixtures with 0.42 w/cm (M1 mixtures).

Table 3. Fresh concrete properties.

Mixture Identifiers	Slump (Inches)	Fresh Air Content (Percent)	Unit Weight (lbs/ft^3)	Temperature (ºF)	Box Test Score
M1 Control	1.00	3.8	151.6	82.2	2
M1 CS-1	1.00	3.3	153.4	79.7	2
M1 CS-2	1.75	3.4	152.3	80.6	2
M1 CS-3	1.00	4.0	152.6	78.6	2
M2 Control	6.75	2.7	150.9	83.1	—
M2 CS-1	6.75	2.4	151.6	83.8	—
M2 CS-2	6.50	2.4	152.4	81.6	—
M2 CS-3	6.50	2.6	151.2	80.7	—

—Test not performed because the target slump is not intended to be used in slipform applications.

Figure 4. Graph. HRWR dosage for each mixture.



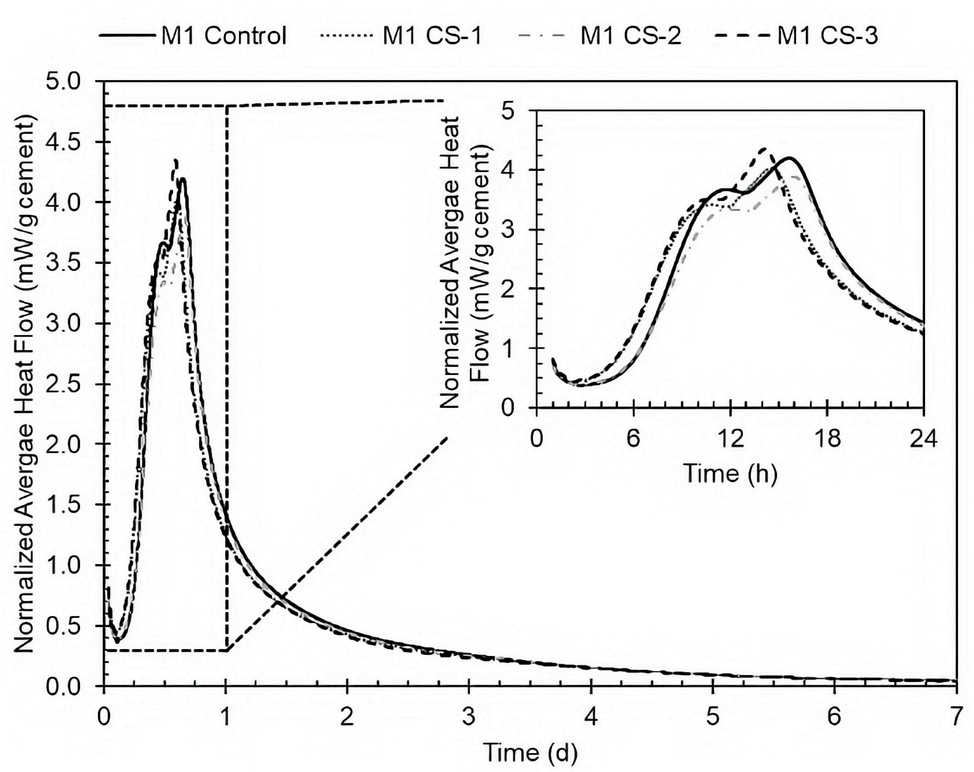
Source: FHWA.

Influence of CS Admixture on Cement Hydration

Hydration kinetics of cementitious paste systems incorporating CS admixtures were measured using isothermal calorimetry performed according to ASTM C1702 for up to 7 d of hydration.(27) The tested paste mixtures incorporated HRWR dosages representative of those used in their corresponding concrete mixtures. Two replicates for each mixture were tested, and the normalized average heat flow for M1 and M2 paste mixtures are shown in figure 5 and figure 6, respectively. In addition, the average cumulative heats released for all mixtures at 1, 3, and 7 d are shown in figure 7. Replicate curves and error bars are not shown in the figures because of the negligible differences between the calorimetry measurements.

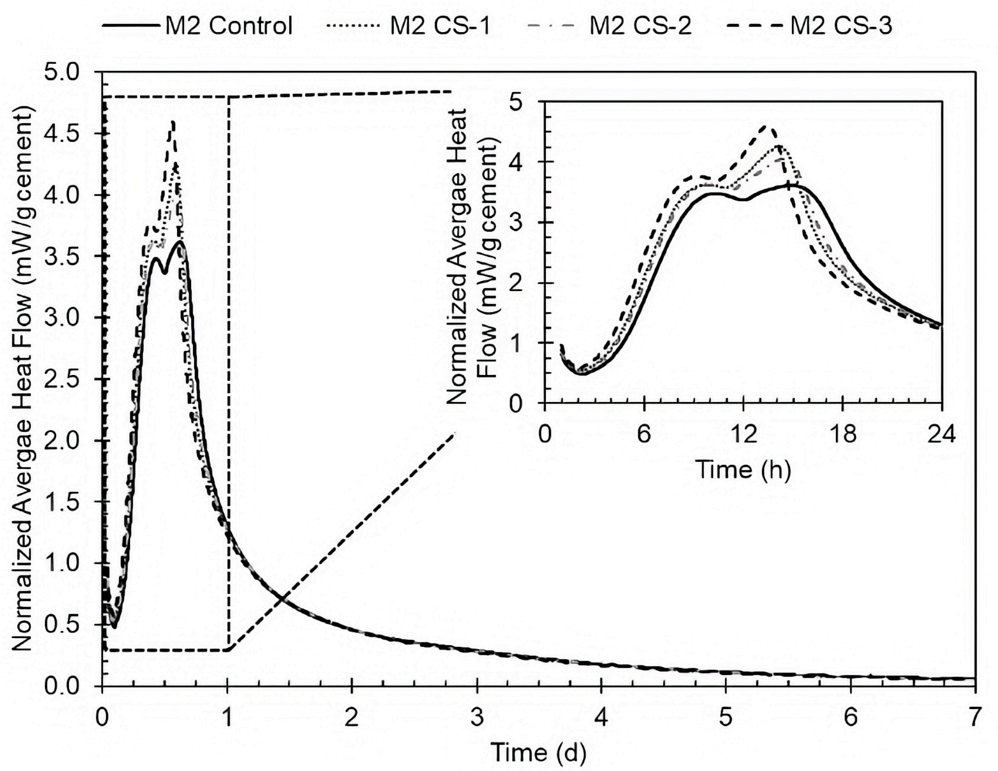
Polycarboxylate-based HRWR was used for all mixtures in this study, and this admixture type is known to retard hydraulic reactions.(29) However, CS is known to act as an accelerator.(30,31) The addition of CS elevated both the alite hydration (peak 1) and the first renewed aluminate hydration (peak 2) peaks in M2 mixtures, but this hydration was not the case for the M1 mixes, possibly due to the higher dosages of polycarboxylate-based HRWR present in the M1 mixtures. In both mixture types (M1 and M2), the first and second peaks were shifted to the left (earlier) in the presence of CS (except M1 CS-2), which is likely the effect of hydration acceleration due to the presence of CS in the mixtures.(29,31) The cumulative heat values at each age ranged within 29 J/g of each other between all eight mixtures, although the M1 mixtures with CS demonstrated nominally lower cumulative heats than the M1 control or M2 mixtures.

Figure 5. Graph. Normalized average heat flow for M1 paste mixtures.



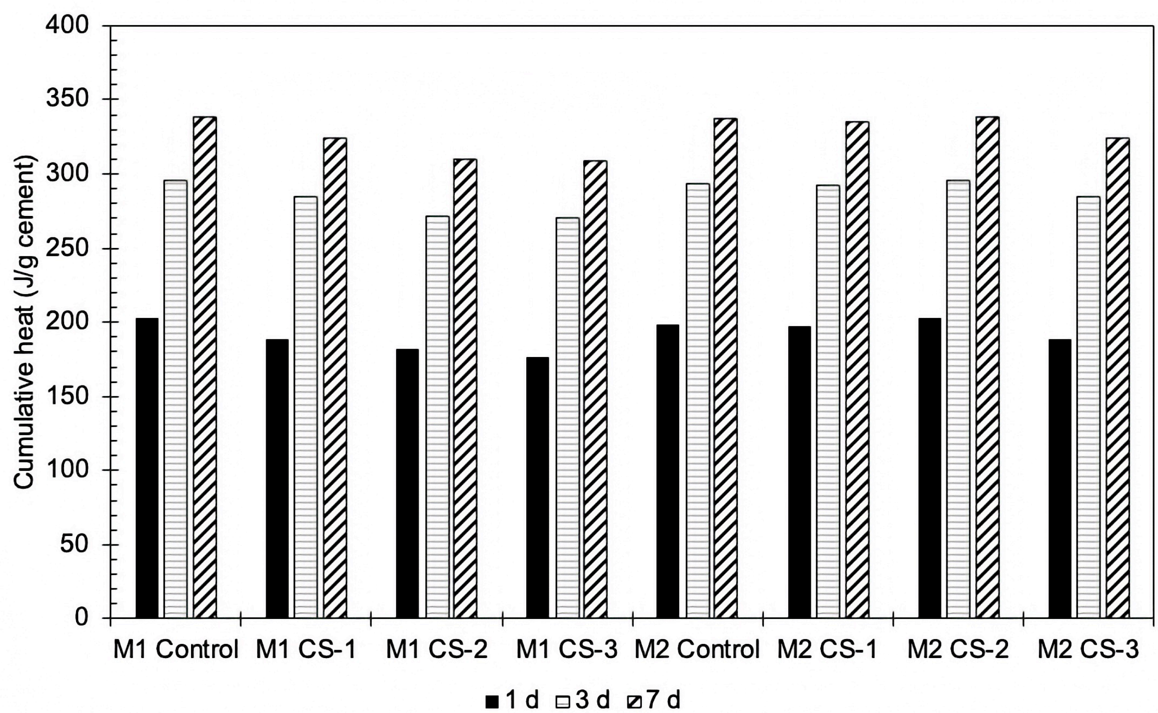
Source: FHWA.

Figure 6. Graph. Normalized average heat flow for M2 paste mixtures.



Source: FHWA.

Figure 7. Graph. Cumulative heats for all cement paste mixtures at 1, 3, and 7 d.

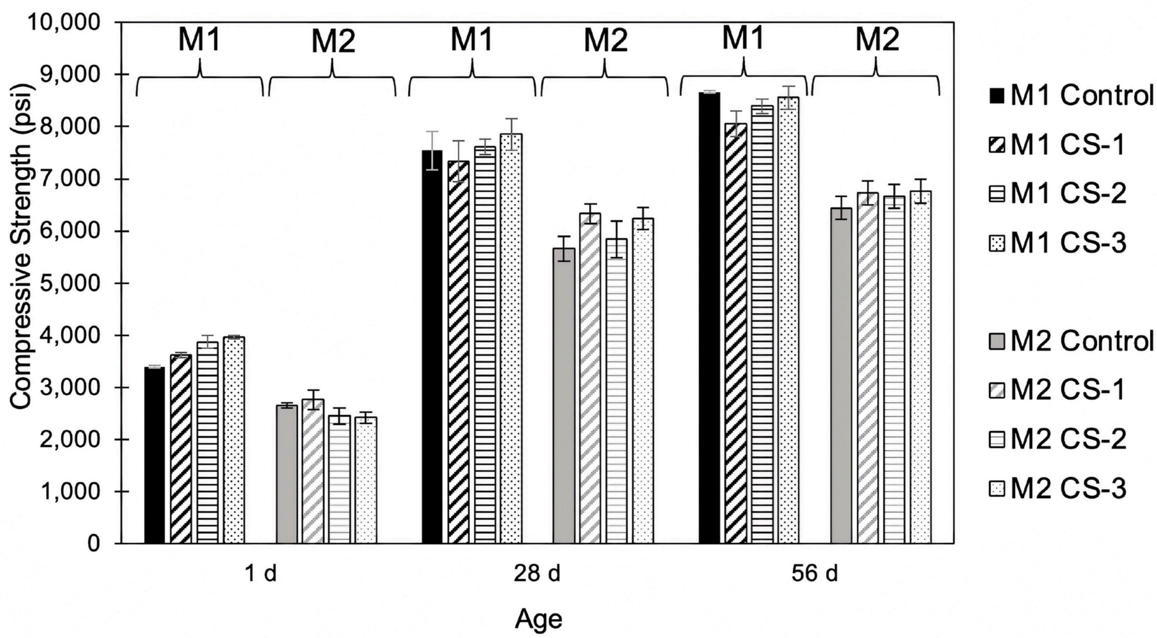


Source: FHWA.

Compressive Strength

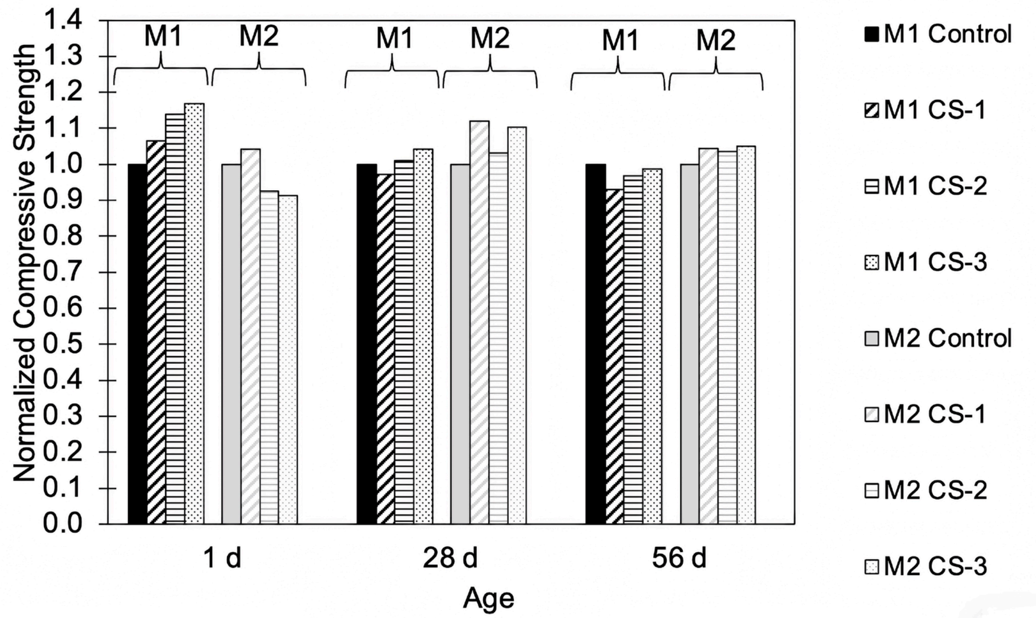
Compressive strengths for each mixture were measured in triplicate at ages of 1, 28, and 56 d in accordance with ASTM C39, and the averages and standard deviations are shown in figure 8.[28] Data were normalized to the compressive strengths of the control mixtures at each age and are shown in figure 9. The 1-d compressive strengths were measured on 4×8-inch cylinders kept in sealed conditions during the first 24 h after casting, while the cylinder samples for 28- and 56-d compressive strength testing were cured in limewater tanks after 24 h. Compressive strengths of concretes incorporating CS were within the ASTM C39 single operator precision of 10.6 percent at 28- and 56-d ages.[28] Incorporation of CS increased the strength at 1-d in M1 mixtures (0.42 w/cm). No statistically significant difference occurred between the control concrete strengths and the averaged strengths of concretes with CS at 28 and 56 d for both concrete mixture types (M1 and M2), showing that the effect of CS on concrete compressive strength diminishes after 1 d. Similar behaviors have been observed in literature with other forms of accelerators.[32,33] This diminishing effect may be due to low dosages of the incorporated CS in concrete mixtures (the highest manufacturer recommended dosage for the dry portion of CS is typically around 0.75 percent by weight of cementitious content), and thus, early consumption of CS is expected.[11,13] As a result, the incorporation of CS does not appear to influence later age or long term mechanical performance.

Figure 8. Graph. Compressive strengths of concrete mixtures at various curing ages.



Source: FHWA.

Figure 9. Graph. Mixture compressive strengths normalized by the relevant control concrete's compressive strength for each age.



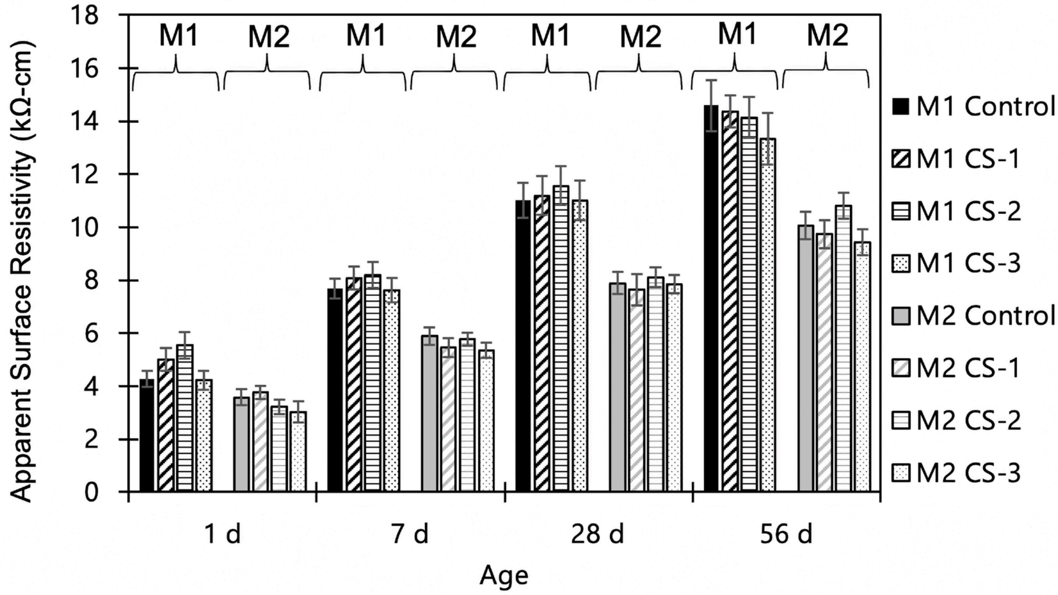
Source: FHWA.

HOW DID THE CONCRETE WITH CS PERFORM IN ELECTRICAL-BASED DURABILITY TESTS IN COMPARISON TO THE CONTROL CONCRETE?

Surface Resistivity

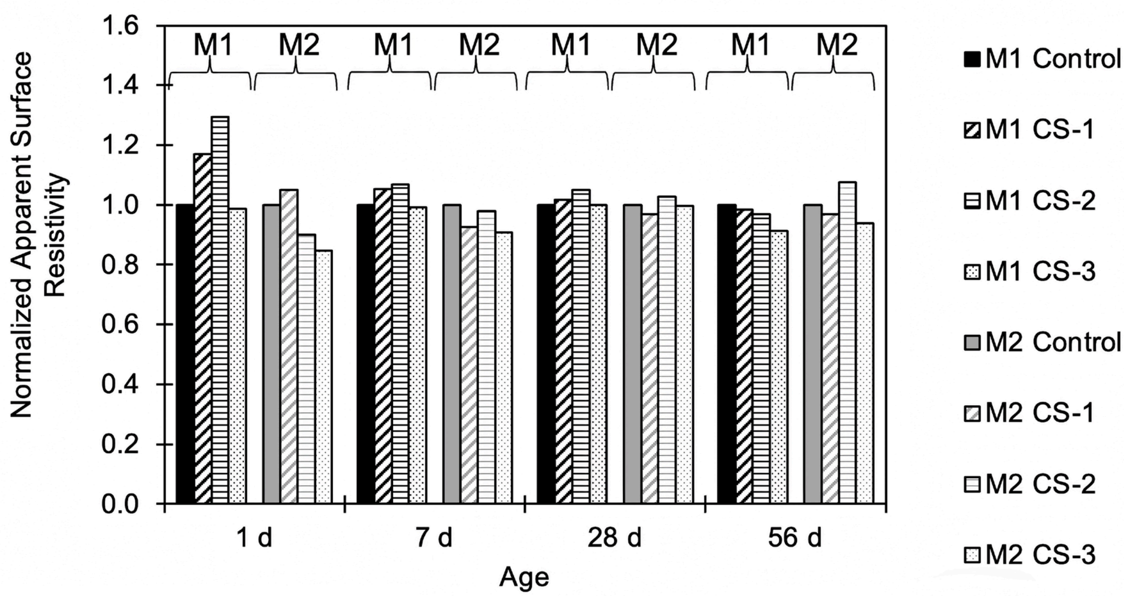
Figure 10 shows the averages and standard deviations for surface resistivity measurements of triplicate samples for each concrete mixture. The data shown in figure 11 were normalized by the apparent surface resistivity of the relevant control mixture for each age. Surface resistivities of concretes incorporating CS were within the single operator precision of 19.1 percent for three measurements at 7-, 28-, and 56-d ages, as determined by multiplying the 5.8-percent coefficient of variation in AASHTO T 358 by 3.3 in ASTM C670 to account for the three samples measured.[1,34] The 0.47 w/cm (M2) concretes exhibited lower resistivities than the 0.42 w/cm (M1) concretes, as expected, because of the higher paste content and w/cm of M2 concretes. Therefore, more fluid and ion transport are likely to occur within the M2 concretes, suggesting lower durability. The apparent surface resistivities for the concretes with CS were not significantly different than those of the control mixtures. However, differences in apparent surface resistivity were visible at 1 d for mixtures containing CS, which is consistent with the compressive strength results and may be a result of the acceleration effects of CS. M2 CS-2 and M2 CS-3 exhibited a lower resistivity than the control at 1 d, although they were within the test method error for single operator precision. M1 CS-1 and M1 CS-2 exhibited higher resistivity values than the control at 1 d. Beyond 1-d testing, the concretes with CS demonstrated similar resistivities to the control concrete, indicating that apparent surface resistivity is not affected by the presence of CS admixtures at ages of 7 d and later.

Figure 10. Graph. Apparent surface resistivity of concrete mixtures at various curing ages.



Source: FHWA.

Figure 11. Graph. Apparent surface resistivities normalized by that of the relevant control concrete mixture at each age.

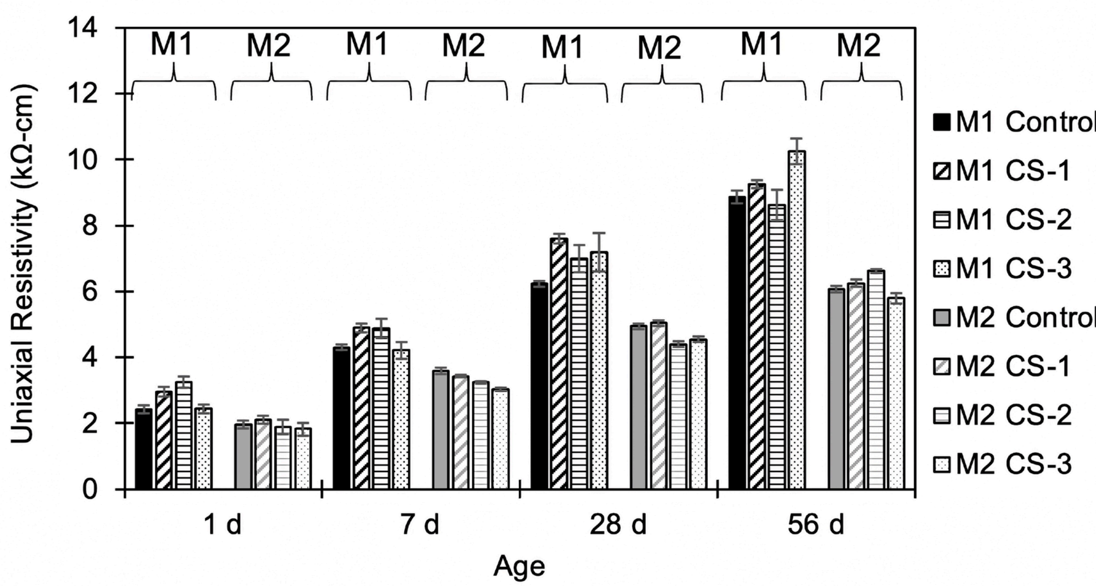


Source: FHWA.

Uniaxial Resistivity

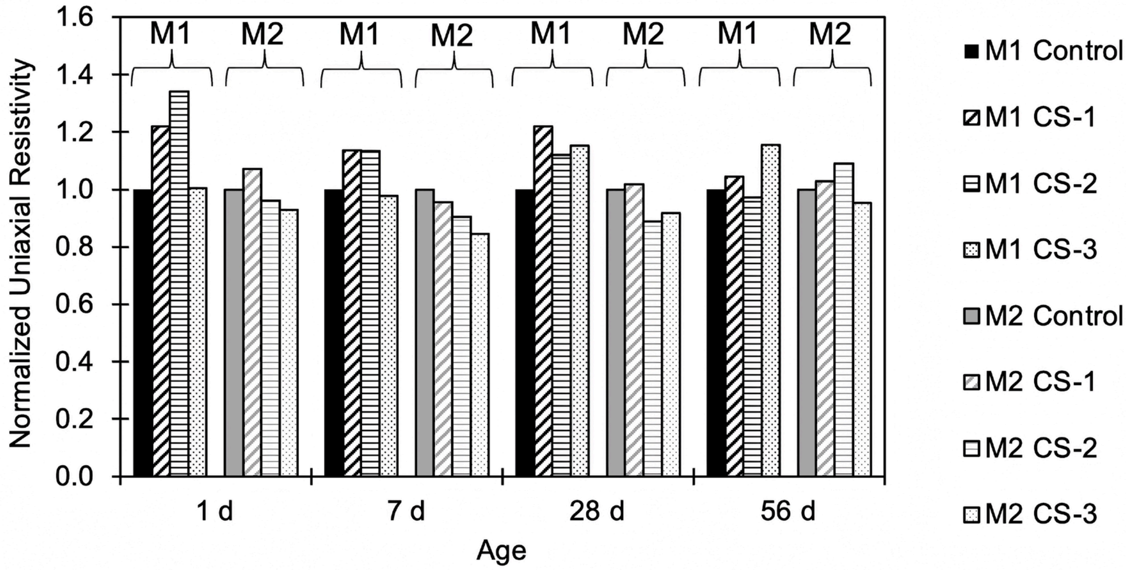
Figure 12 shows the uniaxial resistivities for triplicate samples of each mixture at each age.(2) Figure 13 shows the uniaxial resistivities normalized by that of the control mixture at each age. Uniaxial resistivity demonstrated higher variation than the apparent surface resistivity measurements between the control concretes and those containing CS admixture. Uniaxial resistivity values of concretes incorporating CS were within the single operator precision of 10.9 percent for three measurements at 7-, 28-, and 56-d ages, according to AASHTO T 402 and ASTM C670.(2,34) The difference between the results for materials with and without CS is not larger than the uncertainty expected from testing the same material thrice, suggesting no practically significant difference. The uniaxial resistivities for M1 concretes with CS displayed the same trends as the surface resistivities at 1 d and generally exhibited slightly higher uniaxial resistivities than the M1 control, though the trend for each product was not consistent. The uniaxial resistivities were statistically equivalent (within single-operator precision of the test method) between the M2 control concretes and concretes containing CS. As expected due to the lower paste content and w/cm of the M1 concretes, the M1 concretes exhibited higher uniaxial resistivities than the M2 mixtures. Overall, uniaxial resistivity is not significantly affected by the presence of CS admixture at ages of 7 d and later.

Figure 12. Graph. Uniaxial resistivity of concrete mixtures at various curing ages.



Source: FHWA.

Figure 13. Graph. Uniaxial resistivities normalized by that of the relevant control concrete mixture for each age.



Source: FHWA.

HOW DID THE CONCRETE WITH CS PERFORM IN SEMIELECTRICAL-BASED DURABILITY TESTS IN COMPARISON TO THE CONTROL CONCRETE?

Rapid Chloride Migration

Three concrete cylinders for each mixture were cut after 56 d of limewater tank curing into three pucks, each 2 inches thick, and the rapid chloride migration test was performed according to NT Build 492, using one sample from each cylinder for a total of three samples.[4] The non-steady-state migration coefficients are shown in figure 14 and demonstrate statistical equivalence between the results for the control mixtures compared to those with CS. Non-steady-state chloride migration coefficients of concretes incorporating CS were within the coefficient of variation of reproducibility of 13 percent for three measurements at 56-d ages.[4] The difference between the results for materials with and without CS is not larger than the uncertainty expected from testing the same material thrice, thus demonstrating no practically significant difference.

Figure 15 further exemplifies the statistical equivalence of the apparent surface resistivities of the M1 mixtures to each other and the M2 mixtures to each other. Non-steady-state migration coefficients for concrete with 0.42 w/cm (M1) were lower than for mixtures with 0.47 w/cm (M2), as expected. These results indicate that fluid and chlorides are more easily able to migrate through the M2 concretes than the M1 concretes, and therefore M2 concretes exhibit lower durability performance. Negligible difference between the results for control concretes and concretes containing CS indicate that results of the rapid chloride migration test were not affected by the inclusion of CS admixtures into concrete mixtures. The non-steady-state migration coefficients obtained in this study are on the same order of magnitude as a neat ordinary portland cement mixture defined in the AASHTO *Guide Specification for Service Life Design of Highway Bridges*,[35] which is expected given that the mixture designs in this study use type IL cement with no SCMs.

Figure 14. Graph. Non-steady-state migration coefficients for concrete mixtures after 56 d of curing.

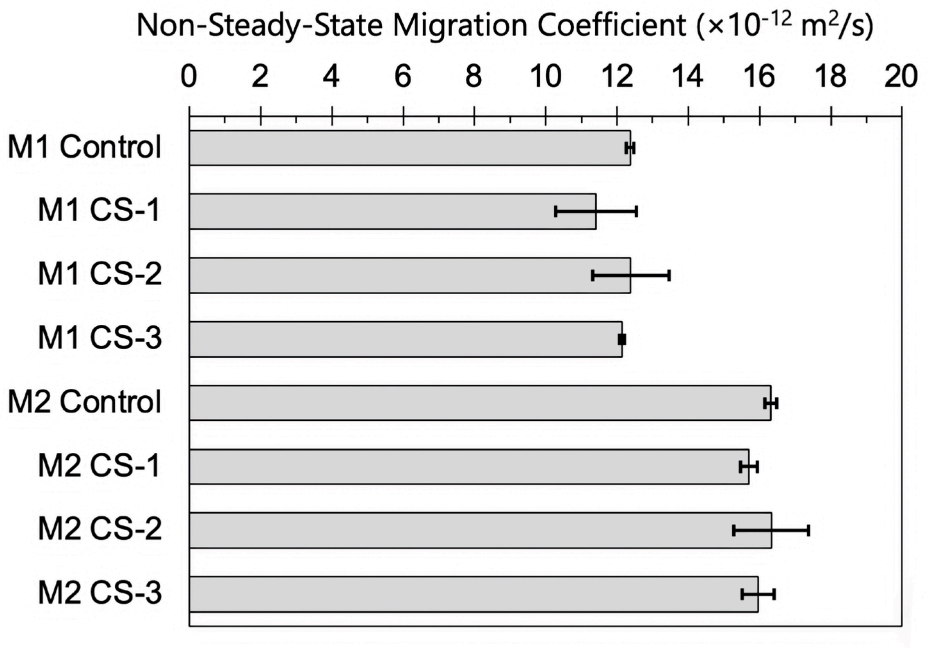


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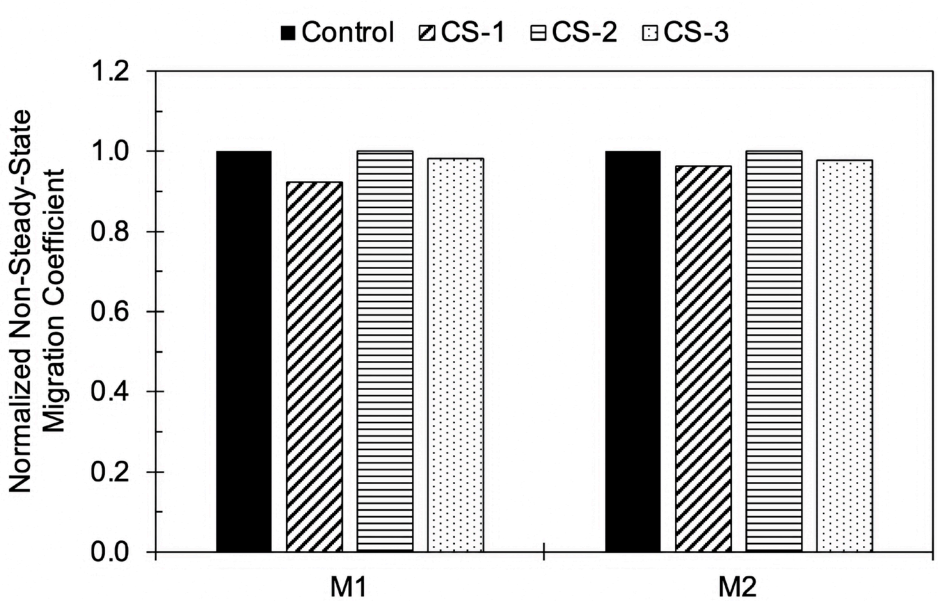
Figure 15. Graph. Non-steady-state migration coefficients after 56 d of curing normalized by the control mixture non-steady-state migration coefficients.



Source: FHWA.

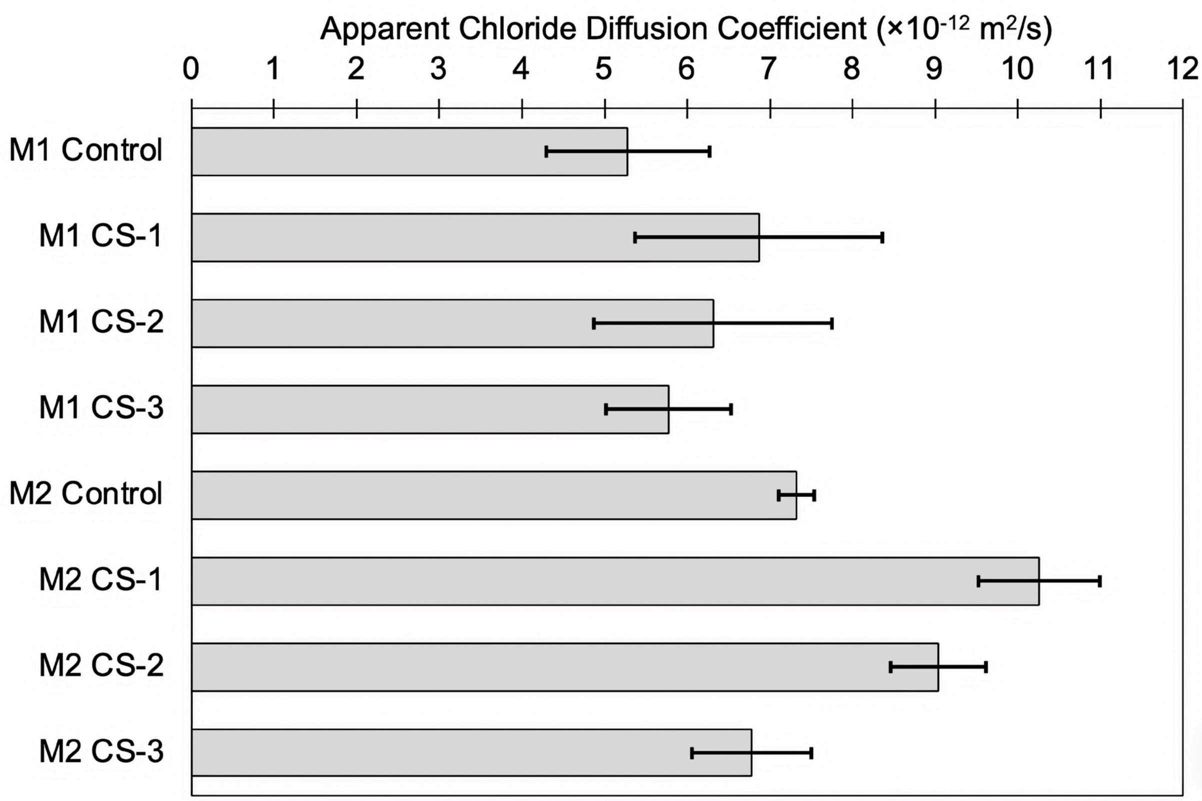
HOW DID THE CONCRETES WITH CS PERFORM IN NONELECTRICAL-BASED DURABILITY TESTS IN COMPARISON TO THE CONTROL CONCRETES?

Bulk Chloride Diffusion

The sample preparation for performing bulk chloride diffusion measurements started after 56 d of curing. Two samples from two different cylinders were cut to 4-inch heights, the sides were epoxy coated, and the samples were placed in a sodium chloride solution for 91 d, in accordance with ASTM C1556.[(6)] The only deviation from the standard method was that both the sample top and bottom were exposed to sodium chloride solution, and both sides were abraded using a 125-needle scaler to simulate the actual surface of the concrete in the field.

Figure 16 displays the averages and ranges of apparent chloride diffusion coefficients for each concrete mixture. As expected, the concretes with lower w/cm (M1) have lower apparent chloride diffusion coefficients than those with higher w/cm (M2). In general, concretes with CS-1 and CS-2 displayed higher apparent chloride diffusion coefficients than their controls, although the values are within the variability of the results for the control mixture at the lower w/cm. The bulk diffusion test results were within the 39.8-percent precision limit (d2s percentage), which is the maximum acceptable difference between the two replicate test results.[(6)]

Figure 16. Graph. Apparent chloride diffusion coefficients, with the error bars representing the minimum and maximum measured values.

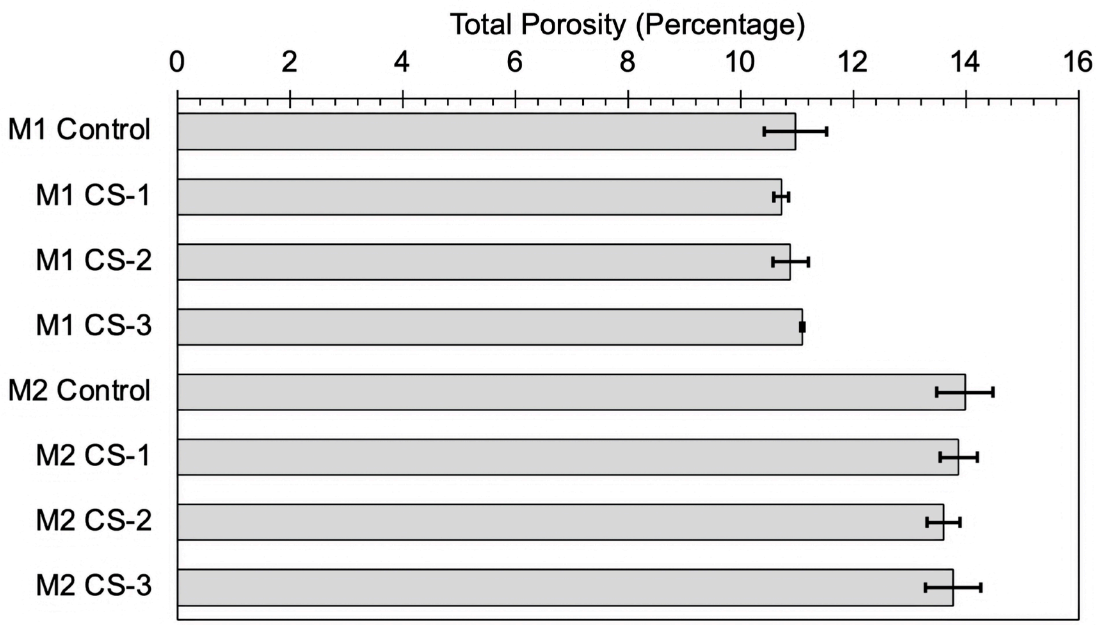


Source: FHWA.

Total Porosity

The total porosity was measured in accordance with ASTM C642, using vacuum saturation approximately 32 mmHg instead of boil saturation, as allowed by Note 2 in ASTM C642 and seen in literature, on three concrete samples after 56 d of age.[22,36] Figure 17 displays the average and standard deviation of total porosity measured for each concrete mixture. Mixtures with the 0.42 w/cm (M1) exhibited lower porosity than the mixtures with the 0.47 w/cm (M2), as expected. The incorporation of CS admixture in concrete demonstrated minimal effects on the total porosity of the concrete mixtures at 56 d.

Figure 17. Graph. Total porosities of concrete mixtures after 56-d ages.



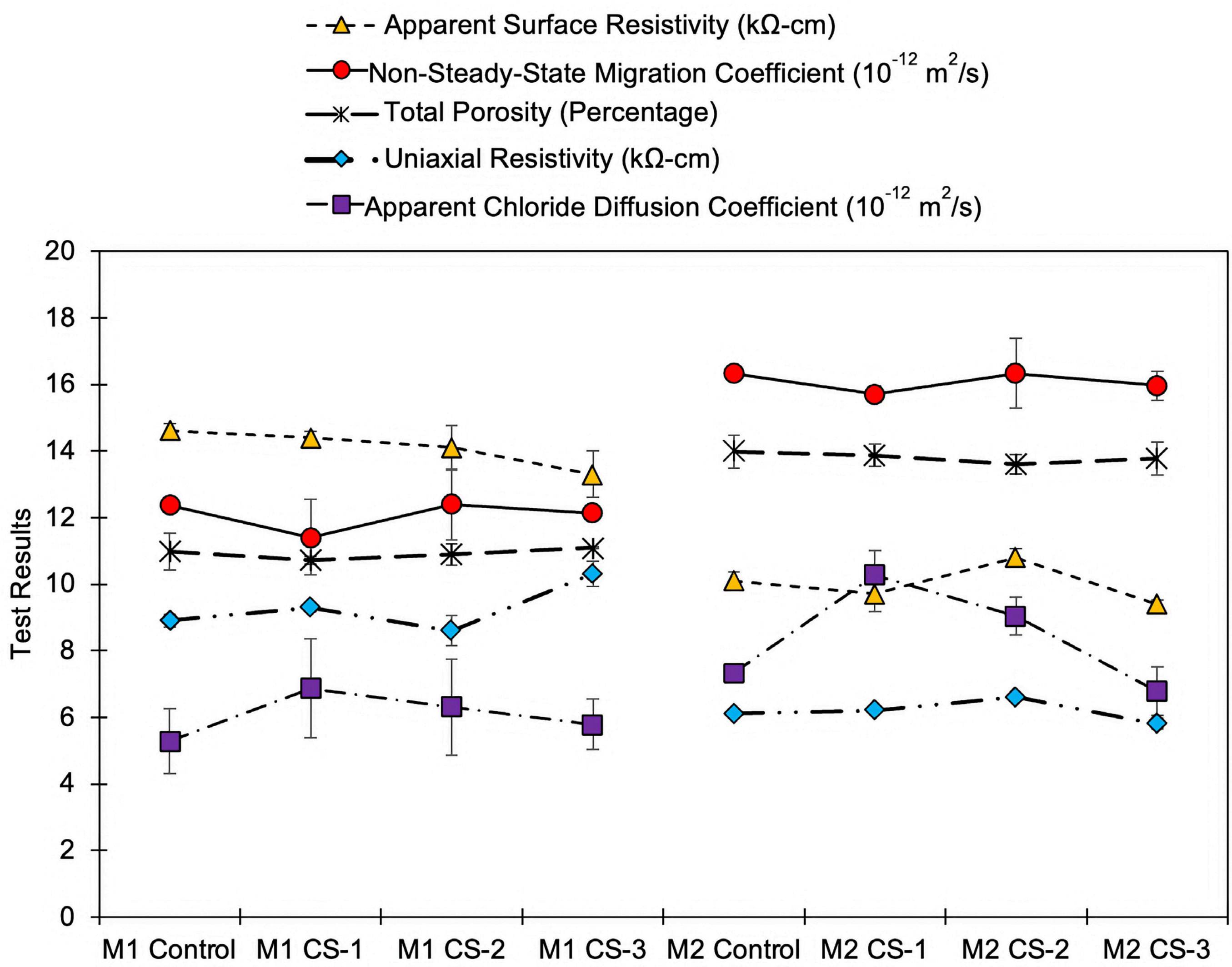
Source: FHWA.

HOW DID THE ELECTRICAL-, SEMIELECTRICAL-, AND NONELECTRICAL-BASED DURABILITY INDICATORS COMPARE?

Considering the premise of this work, this section explores trends in the durability results and compares the results of the electrical-, semielectrical-, and nonelectrical-based durability test methods. Figure 18 depicts the trends in the results from all durability tests, including apparent surface resistivity (electrical), uniaxial resistivity (electrical), rapid chloride migration (semielectrical), bulk chloride diffusion (nonelectrical), and total porosity (nonelectrical) after 56-d ages.

Figure 18 verifies that the trends presented for results from nonelectrical-based durability tests corroborate the trends of the electrical- and semielectrical-based tests. The higher apparent chloride diffusion coefficients of the M2 mixtures with higher w/cm track with higher chloride migration coefficients and lower resistivities of those mixtures. However, the bulk chloride diffusion coefficient was found to be slightly higher than the control for the M2 CS-1 and M2 CS-2 mixtures, which was not seen for resistivity or rapid chloride migration test results. Overall, the electrical-based durability tests can be used to monitor and indicate the durability of concretes containing CS.

Figure 18. Graph. Electrical, semielectrical, and nonelectrical-based test results trends after 56-d ages.



Source: FHWA.

SUMMARY

The purpose of this study was to evaluate the applicability of electrical-based test methods to indicate the durability of concretes containing CS for mixture qualification, quality control, and quality assurance purposes. Three commercially available CS products were incorporated into two concrete mixtures representing pavement and bridge mixtures to evaluate early age and later age durability performance. The summarized findings of this study are as follows:

- Electrical-based tests can indicate the durability of concretes containing CS when the CS content is within the manufacturer's recommended dosages. When performing durability testing on concretes containing CS, test methods such as surface resistivity, uniaxial resistivity, rapid chloride migration, bulk chloride diffusion, and total porosity can be used. If the validity of an electrical test method is in question, then bulk chloride diffusion testing can be performed to indicate the durability of the concrete mixture.
- CS may increase the rate of bulk chloride diffusion in concretes with high w/cm, but it did not cause significant change in the rate of bulk chloride diffusion in concretes with typical-to-low w/cm.
- The electrical-based durability measurements of concretes containing CS showed no significant differences compared to control concretes.
- CS typically had a minimal effect on concrete performance except at an early age of 1 d, where there may be an increase in resistivity at low-to-typical w/cm.
- CS exhibited no effect on the 56-d non-steady-state chloride migration coefficients of concretes when compared to the control concretes without CS.
- CS exhibited no effect on the 56-d total porosity of concretes when compared to the control concretes without CS.
- Concrete mixtures containing CS needed higher dosages of HRWR to achieve the same target slump as the equivalent control mixture.

Based on the findings, FHWA suggests that concrete durability continue to be improved using mixture design optimization tools, such as reducing w/cm and using well-graded aggregates to decrease paste contents. Best practices for concrete mixture design, mixture qualification, mixture acceptance, concrete construction, and concrete curing should continue to be followed, regardless of chemical admixture additions, to develop durable concrete infrastructure.

RELATING CONCRETE DURABILITY TO SAFETY

Improving concrete durability has direct implications for roadway safety. Because concrete constitutes about 17 percent of paved U.S. roadways and about 90 percent of U.S. bridge decks, even modest extensions in service life can substantially reduce the frequency and duration of work zones across the Nation's transportation system.[37,38] The research in this TechNote evaluates concrete durability test methods for applicability when using CS admixtures in the concrete mixture. These findings suggest that well-constructed and properly cured concretes developed using performance-engineered mixture strategies may reduce the need for condition-driven interventions.

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Researchers—This study was conducted by Amir Malakooti, Payam Hosseini, and Scott Muzenski of the Turner-Fairbank Highway Research Center Concrete Laboratory under contract number 693JJ323D000008 and Michelle Cooper of the FHWA Office of Infrastructure Research and Development.

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