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Influence of Hycrete DSS on Virginia Department of Transportation Class A4 Concrete Mix Designs

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16. Abstract

Virginia Department of Transportation (VDOT) Class A4 concrete mixtures containing Hycrete DSS were evaluated to determine the performance of the mixtures with respect to mechanical properties, alkali-silica reactivity, and corrosion of reinforcement. Class A4 concrete is mainly used in bridge decks and has a minimum 28-day compressive strength of 4,000 psi. The permeability of Class A4 concrete is expected to be below 2500 coulombs for resistance to corrosion and other aggressive solutions, and this is mainly achieved by the use of pozzolans or slag. The effects of admixing Hycrete DSS into a typical Class A4 concrete mixture at three dosage levels (0, 1, and 2 gal/yd^3) and with two quantities of fly ash (0 and 159 lb/yd^3) were determined.

The study showed that Hycrete DSS with a defoaming agent achieves air contents that comply with VDOT specifications. In the severe test, some of the specimens had a high weight loss; this was not expected to be a problem because of their high durability factors. Long-term strengths in specimens with similar air contents (within specification) were comparable. The drying shrinkage values were acceptable in all mixtures, and the bond strength values for the mixtures were comparable. Thus, Hycrete DSS had no effect on the bond between fresh and hardened concrete. Resistance to alkali-silica reactivity was improved with the addition of fly ash, but the addition of Hycrete DSS had only a marginal effect.

Although adding Hycrete DSS alone did not improve resistance to rapid chloride permeability, adding Class F fly ash did result in low permeability. Adding Hycrete DSS did lower sorptivity. Further evaluation indicated that adding Hycrete DSS at a sufficient concentration most likely restricts moisture intake and adding fly ash reduces the movement of moisture within the system. Therefore, when these two effects occur together in concrete, chloride movement into the concrete is considerably restricted.

Based on the results of this study, the investigators recommend that VDOT's Structure & Bridge Division continue the use of pozzolans to reduce the influx of chloride ions and increase the life of structures. In addition, VDOT's Structure & Bridge Division should make a trial batch of the Class A4 concrete mixture with Hycrete DSS for placement in a bridge deck to evaluate the field performance of this product. If the field performance confirms the laboratory test results of this study, the use of Hycrete DSS is expected to lead to extended service life and to aid in minimizing maintenance costs. VDOT will spend approximately $15 million for new bridge decks this construction season. Based on a life cycle cost analysis, with a 10 percent increase in the service life of bridge decks or structures, VDOT would save $1.5 million dollars each year through the use of Hycrete DSS.

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ABSTRACT

Virginia Department of Transportation (VDOT) Class A4 concrete mixtures containing Hycrete DSS were evaluated to determine the performance of the mixtures with respect to mechanical properties, alkali-silica reactivity, and corrosion of reinforcement. Class A4 concrete is mainly used in bridge decks and has a minimum 28-day compressive strength of 4,000 psi. The permeability of Class A4 concrete is expected to be below 2500 coulombs for resistance to corrosion and other aggressive solutions, and this is mainly achieved by the use of pozzolans or slag. The effects of admixing Hycrete DSS into a typical Class A4 concrete mixture at three dosage levels (0, 1, and 2 gal/yd^3) and with two quantities of fly ash (0 and 159 lb/yd^3) were determined.

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Although adding Hycrete DSS alone did not improve resistance to rapid chloride permeability, adding Class F fly ash did result in low permeability. Adding Hycrete DSS did lower sorptivity. Further evaluation indicated that adding Hycrete DSS at a sufficient concentration most likely restricts moisture intake and adding fly ash reduces the movement of moisture within the system. Therefore, when these two effects occur together in concrete, chloride movement into the concrete is considerably restricted.

Based on the results of this study, the investigators recommend that VDOT's Structure & Bridge Division continue the use of pozzolans to reduce the influx of chloride ions and increase the life of structures. In addition, VDOT's Structure & Bridge Division should make a trial batch of the Class A4 concrete mixture with Hycrete DSS for placement in a bridge deck to evaluate the field performance of this product. If the field performance confirms the laboratory test results of this study, the use of Hycrete DSS is expected to lead to extended service life and to aid in minimizing maintenance costs. VDOT will spend approximately $15 million for new bridge decks this construction season. Based on a life cycle cost analysis, with a 10 percent increase in the service life of bridge decks or structures, VDOT would save $1.5 million dollars each year through the use of Hycrete DSS.

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INTRODUCTION

The Virginia Department of Transportation (VDOT) allocates considerable resources to address problems associated with chloride-induced corrosion in steel-reinforced concrete structures. To reduce the cost of corrosion, various mitigation techniques have been proposed over the years, with some producing worthwhile results and others being proven to be ineffective.

To protect the reinforcement in concrete, intrusion of chlorides to the level of reinforcement should be prevented. To accomplish this goal, low-permeability concrete and sufficient cover depth are necessary. In Virginia, pozzolans or slag is widely used to lower the permeability of concrete and the minimum cover depth is specified.[1] However, if the quality of the concrete is poor, the cover depth is inadequate, or cracking is sufficient to facilitate the intrusion of chlorides, then chlorides can reach the steel reinforcement. In cases where the chlorides reach the steel, corrosion-resistant reinforcing bars or means of mitigating corrosion at the bar are sought.

One proposed corrosion mitigation technique is the use of corrosion-inhibiting admixtures. In general, manufacturers of inhibiting admixtures suggest this approach reduces corrosion by influencing reactions at the surface of the steel, which results when sufficient quantities of inhibitor contact the reinforcing steel. The inhibitor evaluated in this study is "comprised of an alkali based salt of dioic acid" according to the patent application filed by the manufacturer.[2] The admixture, named Hycrete DSS (DSS), is claimed to be effective against corrosion for two reasons. First, it attaches itself to the steel reinforcement and forms a monomolecular layer over the reinforcement, which protects the steel from corrosive environment. Second, it also blocks the penetration of water by attaching itself to polar particles in the concrete with and without cracks, which prevents the ingress of chlorides to the level of steel.

Concrete with DSS has been evaluated in laboratory tests by several organizations. The University of Massachusetts Department of Civil and Environmental Engineering and the Rhode Island Department of Transportation conducted a series of tests comparing 14 concrete mixes containing various combinations of calcium nitrite, silica fume, fly ash (FA), slag, and DSS and a concrete mix without any admixture serving as a control. They reported that the only mixes that consistently performed better than the non-cracked control in terms of corrosion activity and amount of chloride present were those containing DSS. In addition, the DSS far outperformed all other admixtures in cracked specimens in iron loss ratings.[3]

The University of Connecticut School of Engineering found that DSS compared favorably in tests with other inhibitors and controls. DSS outperformed calcium nitrite in corrosion rate testing and in chloride penetration testing.[4]

DSS is also being incorporated into applications in the field. The Kansas DOT and the New Jersey Turnpike Authority used DSS as a demonstration material in recent high-profile construction projects.[5] The University of Massachusetts is currently conducting a study involving DSS concrete in several major construction projects throughout New England.[5]

PURPOSE AND SCOPE

The purpose of this study was to evaluate the effects of DSS on the properties of concrete and in reducing the corrosion of reinforcing steel in concrete. In this study, a commonly used Virginia Department of Transportation (VDOT) Class A4 concrete mix design, which is mainly used for bridge decks, was compared with other similar mix designs containing DSS in laboratory specimens. Class A4 mixtures contain pozzolans, have a 28-day minimum compressive strength of 4,000 psi, and are expected to have a maximum permeability of 2500 coulombs.

Comparisons were based on the mechanical properties, the ability to bond to existing concrete, resistance to alkali-silica reactivity (ASR), and resistance to corrosion of the embedded steel.

METHODOLOGY

Overview

Five concrete mixtures were tested:

1. Class A4 mixture with FA used as the control

2. experimental mixture containing DSS at the upper recommended DSS dosage limit with FA

3. experimental mixture containing DSS at the upper recommended DSS dosage limit without FA

4. experimental mixture containing DSS at the lower recommended dosage limit with FA

5. experimental mixture containing DSS at the lower recommended dosage limit without FA.

Concretes were tested at the fresh and hardened states for their material properties and corrosion resistance. An additional mixture was prepared and placed on top of an existing concrete surface to determine the effect of DSS on the bonding of fresh concrete to hardened concrete. Some of the beam specimens for the corrosion resistance were cracked, initially ponded with salt solution in the laboratory, and then moved outdoors to determine the effect of environmental change.

Laboratory Testing

Mixture Proportions

The mixture proportions for the five mixes are shown in Table 1. FA was used with a Type I/II portland cement (PC) as the control. The FA used in this study was Class F (ASTM C 618). Coarse aggregate was granite gneiss with a nominal maximum size (NMS) of 1 in. Fine aggregate was natural sand. DSS was used in two dosages: one at 2 gal/yd^3 (15.4 lb/yd^3) designated "DSS" and the other one at 1 gal/yd^3 (7.7 lb/yd^3) designated "0.5DSS."

For each variable, three batches of concrete were made to accommodate the amount of concrete needed to make the specimens. The pan-type mixer used had a 2 ft^3 capacity, with each batch having a volume of 1.75 ft^3. Specimens for each variable were tested for their mechanical properties, alkali-silica reactivity (ASR), and corrosion resistance. Fresh concrete tests included slump (ASTM C 143), air content (ASTM C 231), unit weight (ASTM C 138), and mix temperature (ASTM C 1064). The tests for hardened concrete are summarized in Table 2. The tests were performed on concrete specimens with the 1-in NMS coarse aggregate except that the overlay in the bond test had the ½-inch NMS coarse aggregate, since the overlay thickness was 2 in. Another exception was the use of mortar specimens for the test for ASR (ASTM C 1260).

Table 1. Mixture Proportions for Each Variable (lb/yd^3)

Material	PC/FA/DSS	PC/FA	PC/DSS	PC/FA/0.5DSS	PC/0.5DSS
PC (I/II)	477	477	636	477	636
Class F fly ash	159	159	0	159	0
Coarse aggregate	1868	1868	1868	1868	1868
Fine aggregate	1068	1068	1117	1069	1128
Water	285	285	285	285	285
Hycrete DSS	15.4	0	15.4	7.7	7.7
w/cm	0.45	0.45	0.45	0.45	0.45

Note: For DSS mixtures, a defoaming agent provided by the manufacturer was used to comply with the specification limits of 6.5 $\pm$ 1.5% air content. Mixtures without DSS contained a commercially available air-entraining admixture to comply with the air content requirements. In some mixtures, a high-range water-reducing admixture was added to provide workability.

Table 2. Hardened Concrete Tests

Test Standard	Information Provided	Test Dates	No. of Specimens (Specimen Type)	Specimen Dimensions
ASTM C 39	Compressive strength	24 hr, 7 days, 28 days, 90 days, 1 yr	3 (PC/FA) 3 (PC/FA/DSS) 3 (PC/DSS)	4 in x 8 in cylinder
ASTM C 469	Elastic modulus	24 hr, 7 days, 28 days, 90 days, 1 yr	N/A: Use data from strength test	N/A
ASTM C 496	Splitting tensile strength	24 hr, 7 days, 28 days, 90 days, 1 yr	3 (PC/FA) 3 (PC/FA/ DSS) 3 (PC/DSS)	4 in x 8 in cylinder
ASTM C 1202	Permeability	28 days	3 (PC/FA) 3 (PC/FA/DSS) 3 (PC/DSS)	4 in x 4 in cylinder
ASTM C 157	Drying shrinkage	4 days, 7 days, 14 days, 28 days, 8 wk, 16 wk, 32 wk, 1 yr.	3 (PC/FA) 3 (PC/FA/DSS) 3 (PC/DSS)	3 in x 3 in x 11 in beam
ASTM C 666	Freeze-thaw	Every 50 cycles	3 (PC/FA) 3 (PC/FA/DSS) 3 (PC/DSS)	3 in x 4 in x 16 in beam
ASTM C 1260	ASR susceptibility (mortar-bar method)	2 days (zero reading), 4 days, 7 days, 10 days, 14 days	3 (PC/FA) 3 (PC/FA/DSS) 3 (PC/DSS)	1 in x 1 in x 11.25 in beam
ASTM C 1585	Absorption rate	60 sec, 5 min, 10 min, 20 min, 30 min, 1 hr, 2 hr, 3 hr, 4 hr, 5 hr, 6 hr, 1 day, 2 days, 3 days, 4 days, 5 days, 6 days, 8 days	3 (PC/FA) 3 (PC/FA/DSS) 3 (PC/DSS)	4 in x 8 in cylinder
ASTM G 109	Corrosion	Every other week	9 (PC/FA) 9 (PC/FA/DSS) 9 (PC/DSS)	4.5 in x 6 in x 11 in beam

The corrosion tests were conducted in accordance with ASTM G 109, with the multimeter connected so that negative voltage measurements corresponded to a positive galvanic current. Of 10 specimens cast for each batch, 5 were cracked and 5 were left uncracked. To crack the specimens, the beams were loaded in flexure upside down so that the top surface was in tension. A 0.025-in-thick shim was inserted into the crack to keep it open. A dike was built on top of the specimens for ponding. The specimens were ponded every other week with 3 percent calcium chloride solution in the laboratory for approximately 8 months, and then they were exposed outdoors. Outdoor dry and wet days with fluctuating temperatures provided varying environmental conditions. Periodically, the macrocell corrosion rate was measured in accordance with ASTM G 109. After the testing was completed, some of the cracked specimens were autopsied to evaluate visually the condition of the reinforcement. From the uncracked specimens, powdered specimens for the chloride content measurements were obtained at different depths. To ensure the specimens were relatively free of chloride prior to ponding, the background chloride content before ponding was also determined.

To evaluate the movement of chloride ions into the concrete, the effective diffusion coefficient (D_{eff}) was determined (based on Fick's second law) for each mix design. To solve Fick's second law and calculate D_{eff}, it was assumed that the chloride concentration at the surface (C_s) was constant and the slab had a semi-infinite thickness. Under these conditions, the solution to Fick's second law is given by Eq. 1.

$$C(x,t) = C_S \, erfc\left(\frac{x}{2\sqrt{D_{eff}\, t}}\right) \quad \text{[Eq. 1]}$$

where

C(x,t)	=	chloride concentration as a function of depth and time
C_s	=	chloride concentration on concrete surface
x	=	depth measured from surface toward rebar
D_{eff}	=	effective diffusion coefficient
t	=	time.

The value of the complementary error function was then estimated using the following relationships given in Eq. 2:

$$erfc(z) = 1 - erf(z) \quad \text{[Eq. 2]}$$

A software program, Probability Based Corrosion Service Life Prediction, written by R. E. Weyers, G. S. Williamson, W. Yaw, L. Liang, C. Anderson-Cook, and T. J. Kirkpatrick at Virginia Polytechnic Institute & State University uses this approach to solve for the effective diffusion coefficient, functioning as an Excel add-on. Using the program, the effective diffusion coefficient was calculated for each mix design based on the acid-soluble chloride concentration with samples gathered at 0.25-in-depth increments.

The bond strength between the overlay concrete and the existing concrete was evaluated in accordance with ACI 503R-93, Appendix A. The existing base concrete was a typical bridge deck concrete that had gained its required strength. The surface was grit blasted and saturated with water, and an overlay placed. Two overlays were used: one was PC/FA (portland cement and FA) and the other was PC/FA/DSS (portland cement, FA, and Hycrete DSS). After the overlay gained its strength, the top layer was drilled using a 2 1/4 in drill bit down to about 1/2 in into the base concrete. A steel pipe nipple was glued to the top of the core by epoxy. The assembly was pulled in tension to measure the bond strength at 28 days of age for the overlay.

RESULTS AND DISCUSSION

The fresh concrete properties of slump, air content, unit weight, and concrete temperature are given in Table 3, as an average of the three batches. Concretes were workable and easily consolidated on a vibrating table. Air contents of mixtures with DSS were generally closer to the upper limit of the specifications. As expected, an increase in air content resulted in a decrease in the unit weight for each batch, as shown in Figure 1.

Table 3. Fresh Concrete Properties as Average of Three Batches

Property	PC/FA/DSS	PC/FA	PC/DSS	PC/FA/0.5DSS	PC/0.5DSS
Slump (in)	3.4	2.9	2.3	3.3	2.2
Air (%)	8.2	5.4	6.5	7.1	6.7
Unit weight (lb/ft^3)	141.7	146.1	146.3	143.3	145.6
Mix temp. (^oF)	75	75	75	75	76

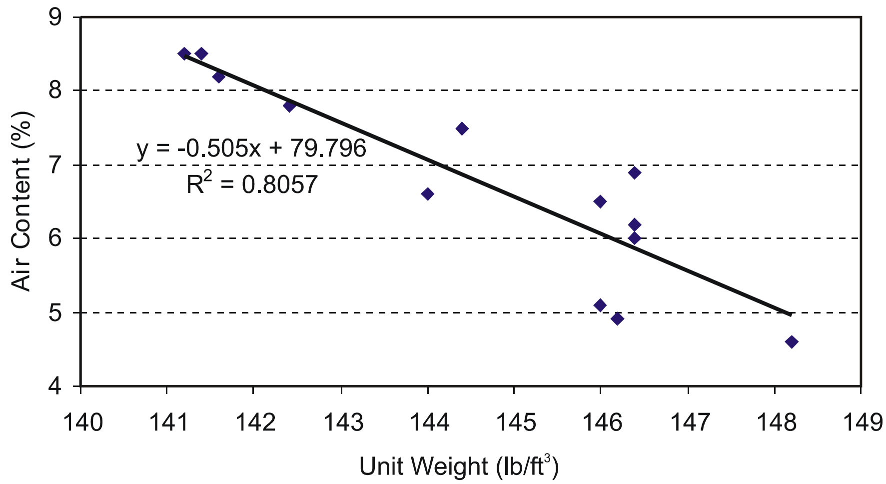


Figure 1. Air Content Versus Unit Weight

The results for the hardened specimens for compressive strength, elastic modulus, splitting tensile strength, permeability, and drying shrinkage are shown in Table 4. Figure 2 displays the strength development. At 28 days, the concretes had difficulty in reaching the

Table 4. Hardened Concrete Properties

Property	Age (days)	Batch (Concrete)				
		B1 (PC/FA/DSS)	B2 (PC/FA)	B3 (PC/DSS)	B4 (PC/FA/0.5DSS)	B5 (PC/0.5DSS)
Compressive strength (psi)	1	1,240	1,490	2,480	1,290	2,260
	7	2,040	2,760	3,480	2,590	3,570
	28	2,980	3,720	4,110	3,510	3,850
	90	3,670	4,530	4,610	4,320	4,970
	365	4,475	5,100	5,410	4970	5,530
Elastic modulus (10^6 psi)	7	2.37	2.58	2.82	2.49	2.78
	28	2.48	2.90	3.00	2.97	2.98
	90	2.99	3.40	3.48	3.40	3.61
	365	3.48	3.80	3.57	4.02	4.46
Splitting tensile strength (psi)	1	200	220	275	205	300
	7	240	320	405	295	395
	28	355	380	450	355	415
	90	405	470	475	450	450
	365	465	465	505	530	580
Permeability (coulombs)	28	1507	1473	4365	1769	5703
Shrinkage (microstrain)	28	363	387	293	377	400
	112	583	543	500	600	587

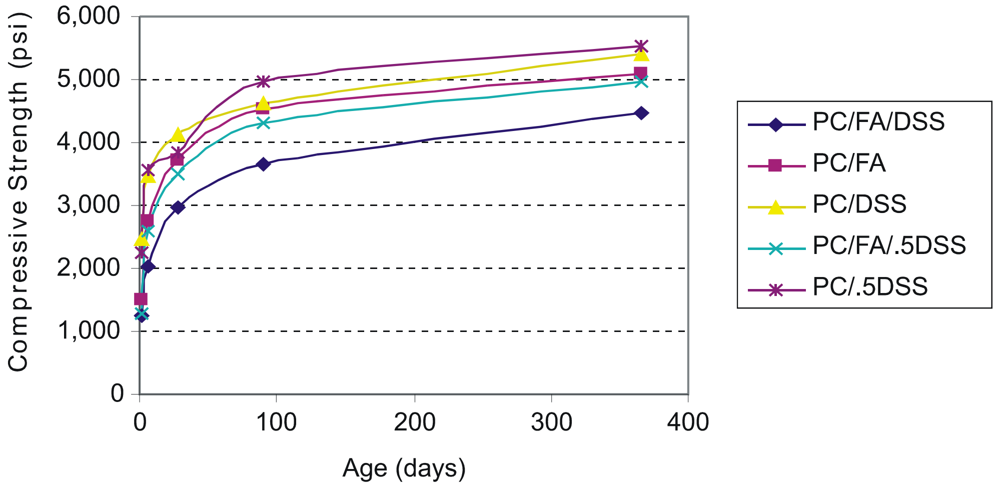


Figure 2. Compressive Strength Development

minimum strength requirement of 4,000 psi. However, at 1 year, the strengths were about 4,500 psi or more. Batch 1 (B1) differed from Batch 2 (B2) because of the addition of DSS and had an average air content of 8.2 percent, compared to 5.4 percent for B2, the control. The difference in the 28-day compressive strength between B2 and B1 was 20 percent at 28 days, 19 percent at 90 days, and 12 percent at 1 year. The difference at 1 year can be attributed to the higher air content in B1; however, at earlier ages, the differences were higher than would be expected from the difference in air content. Thus, the strength development appears to be slowed in the DSS mixtures but catches up with the controls with time. The general rule is that each 1 percent increase in air results in a 5 percent decrease in strength.[6] The addition of more defoamer in B1 would reduce the average air content to the target value and improve the strength to the level of the control as seen in the other DSS mixtures.

The long-term splitting tensile strengths were equal or better in the mixtures with DSS. The chloride permeability of the concretes with FA or with DSS and FA was low, whereas that of those without FA but with DSS was high. These results did not show any beneficial effect of DSS on the permeability of the concretes. It can be thought that the DSS is ionic and affects the electrical conductance and thus the coulomb values. However, the mixture with FA and DSS had a low permeability similar to that of the control mixture with FA only, indicating that the effect of DSS was minimal. The results of the capillary absorption test (ASTM C 1585) are displayed in Figure 3. ASTM C 1585 measures the rate of absorption of water into the capillary pore system at a standard degree of saturation and thus provides a measure of fluid ingress and movement in concrete. In this test, mixtures with DSS had lower absorption rates than did the PC/FA mixtures. The PC/FA mixtures had the highest absorption; however, the permeability value was lowest, indicating easy moisture intake but difficult transport through the concrete.

The DSS mixtures also influenced the reinforced concrete when corrosion-related testing was considered. The cracked specimens in this test (ASTM G 109) provided an indication of the corrosion activity in the various mix designs almost immediately after exposure. Table 5 provides a summary of the charge passed based on the macrocell measurements. As is evident from this table, PC/FA/DSS, which contains FA and 2 gal/yd^3 DSS, had the lowest level of current pass between the reinforcing steel. The PC/DSS, PC/FA/0.5DSS, and PC/0.5DSS mixtures had similar mean values of charge passed, whereas the PC/FA mixture, which

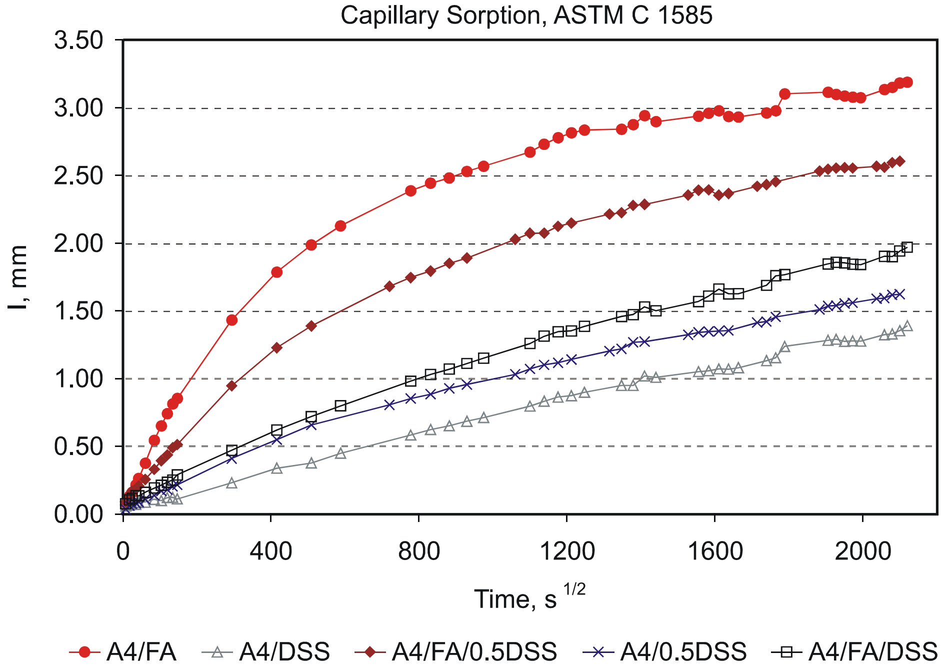


Figure 3. Absorption Rate of Concretes (ASTM C 1585)

Table 5. Charge Passed for Cracked Concrete Specimens (ASTM G 109) Exposed to Inside Laboratory Conditions

Mix Design	Description	Charge Passed, C[a]
PC/FA/DSS	Median	–0.4
	Mean	–37.2
	St. Dev.	82.1
PC/FA	Median	–1265.2
	Mean	–1235.4
	St. Dev.	166.2
PC/DSS	Median	–235.0
	Mean	–409.9
	St. Dev.	642.2
PC/FA/0.5DSS	Median	–1.7
	Mean	–506.8
	St. Dev.	697.8
PC/0.5DSS	Median	–592.0
	Mean	–621.5
	St. Dev.	639.9

[a]The calculation is based on 210 days for the PC/FA/DSS laboratory specimens and 214 days for the other specimens.

contained only FA, had the highest average quantity of charge passed. It is also evident that the use of 2 gal/yd^3 DSS in conjunction with the FA yielded the best results. However, as shown in Table 6, upon moving the specimens outside, the charge passed increased substantially in the PC/FA/DSS specimens. These specimens still maintained the lowest amount of charge passed on average relative to the other mixtures, but it appears the outdoor exposure had an impact. Finally, it is interesting to note that the PC/FA/0.5DSS specimens had results similar to those of the PC/FA/DSS specimens during the outdoor exposure and these are the only mix designs that included both FA and DSS. Finally, the PC/FA mix had results similar to those of the PC/DSS mix but a lower amount of charge passed compared to the PC/0.5DSS mixture. Tables 5 and 6 provide an idea of the variability between specimens during this study, which can also be seen in Figures 4 through 13.

Table 6. Amount of Charge Passed for Cracked Concrete Specimens (ASTM G 109) Subjected to Outside Exposure

Mix Design	Description	Charge Passed, C[a]
PC/FA/DSS	Median	–326.4
	Mean	–330.0
	St. Dev.	226.3
PC/FA	Median	–609.3
	Mean	-589.3
	St. Dev.	133.0
PC/DSS	Median	–648.5
	Mean	–647.9
	St. Dev.	672.5
PC/FA/0.5DSS	Median	–171.5
	Mean	–356.3
	St. Dev.	388.5
PC/0.5DSS	Median	–1109.9
	Mean	–839.0
	St. Dev.	648.3

[a]Calculation based on 132 days of macrocell data.

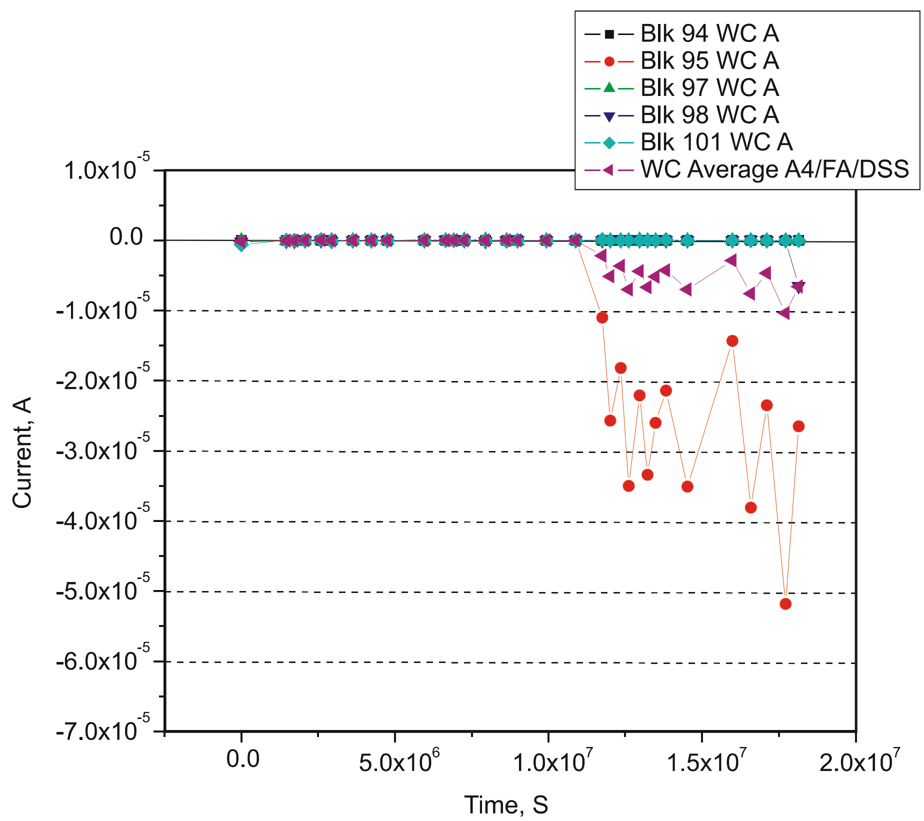


Figure 4. PC/FA/DSS Cracked Specimens Demonstrated Fairly Good Corrosion Resistance During Laboratory Exposure Based on Macrocell Measurements

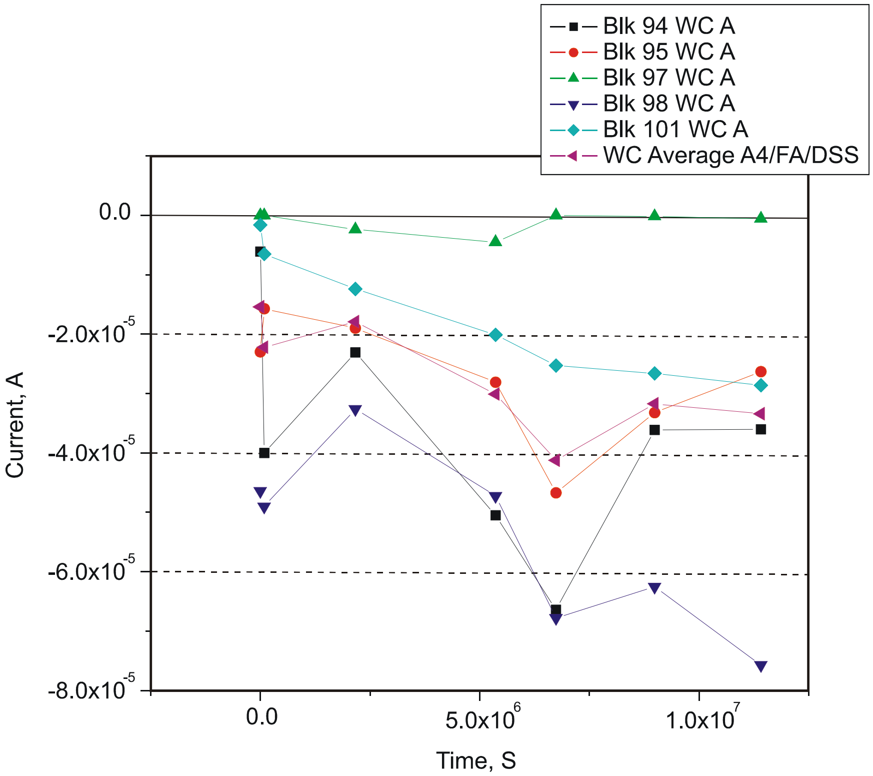


Figure 5. PC/FA/DSS Cracked Specimens Demonstrated an Increase in Corrosion Activity During Outside Exposure Based on Macrocell Measurements

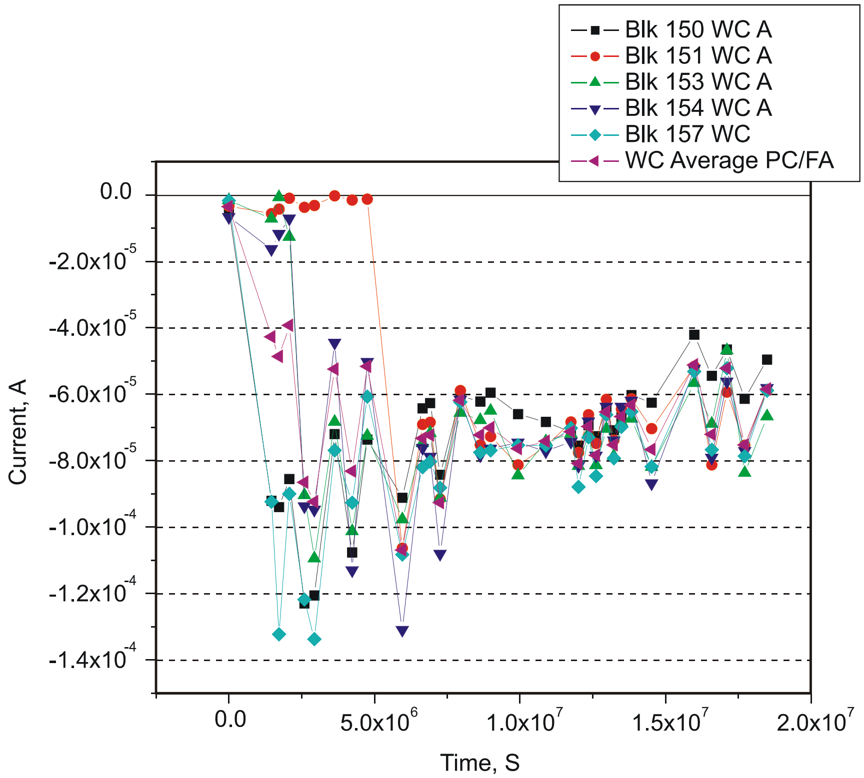


Figure 6. PC/FA Cracked Specimens Demonstrated Worst Corrosion Resistance During Laboratory Exposure

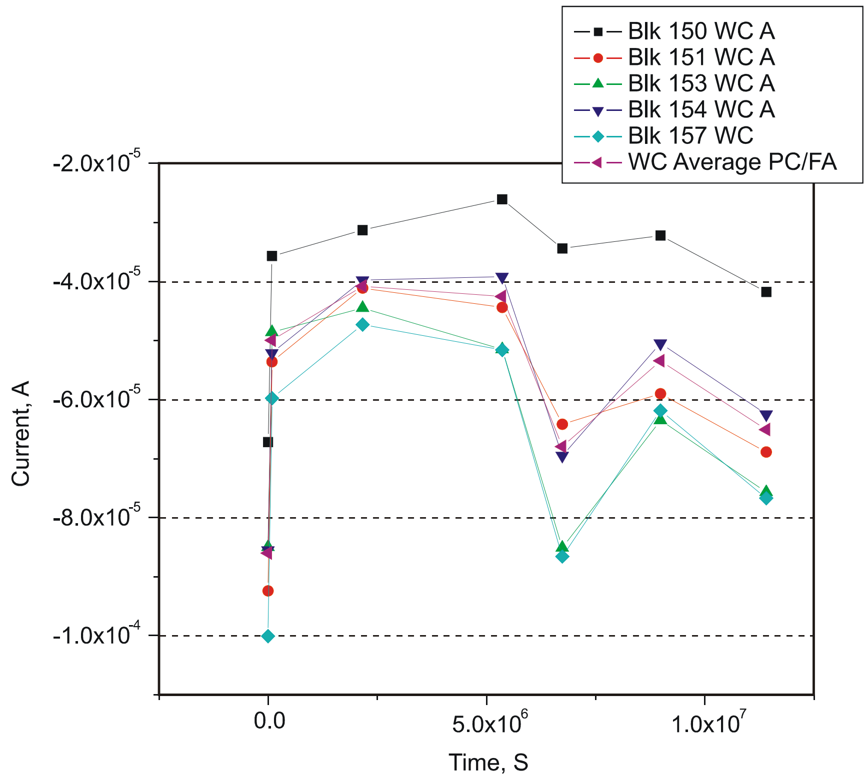


Figure 7. PC/FA Cracked Specimens Displayed Corrosion Activity During Outside Exposure Based on Macrocell Measurements

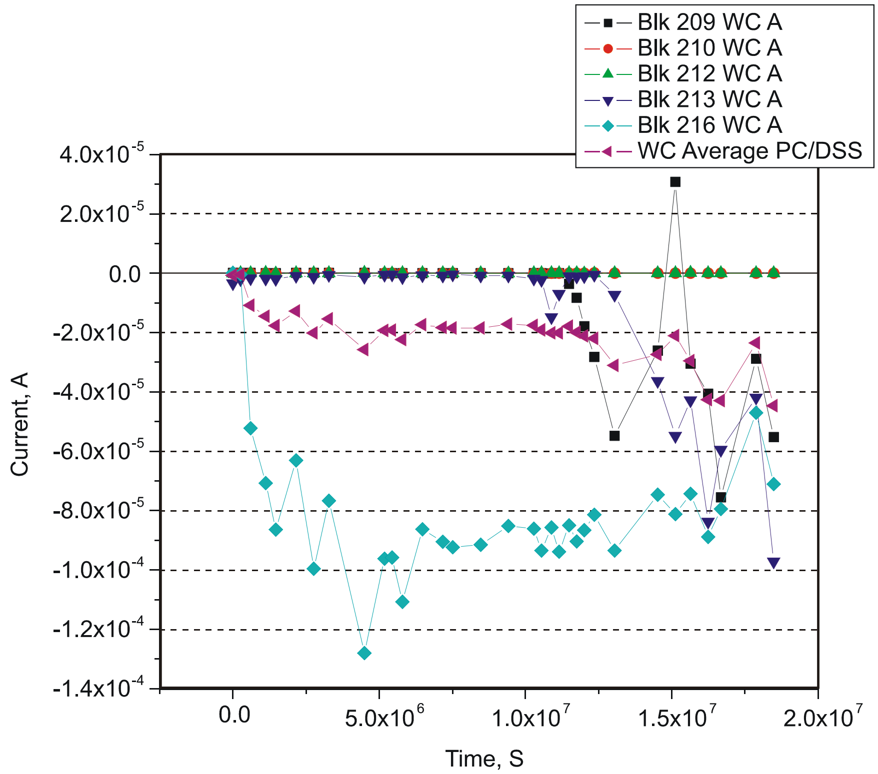


Figure 8. PC/DSS Cracked Specimens Demonstrated Intermediate Good Corrosion Resistance During Laboratory Exposure Based on Macrocell Measurements

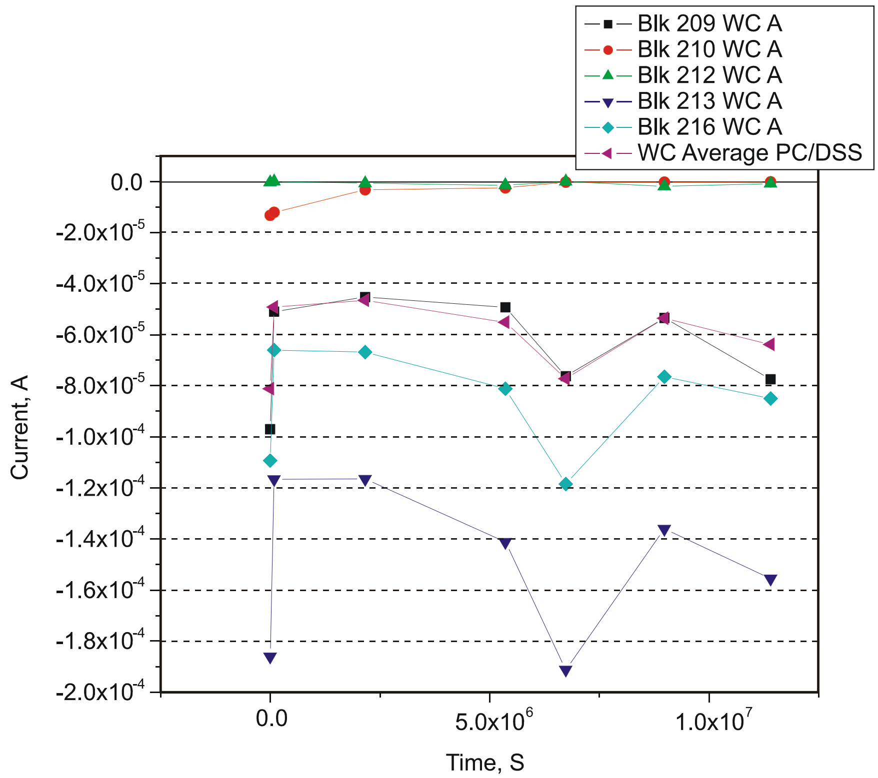


Figure 9. PC/DSS Cracked Specimens Demonstrated Increased Corrosion Activity During Outside Exposure Based on Macrocell Measurements

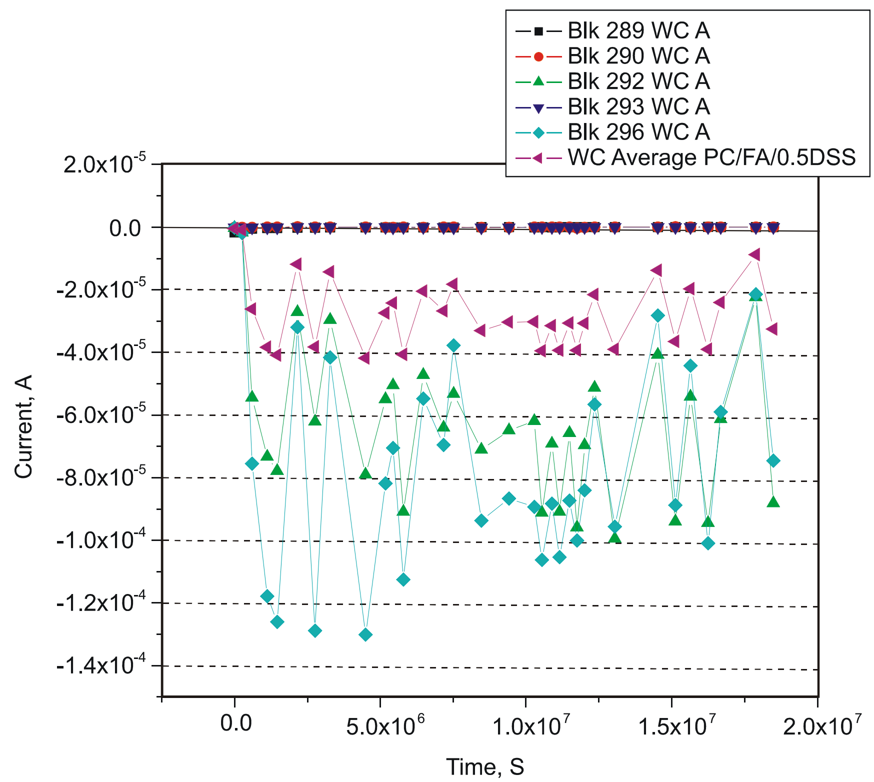


Figure 10. PC/FA/0.5DSS Cracked Specimens Demonstrated Intermediate Good Corrosion Resistance During Laboratory Exposure Based on Macrocell Measurements

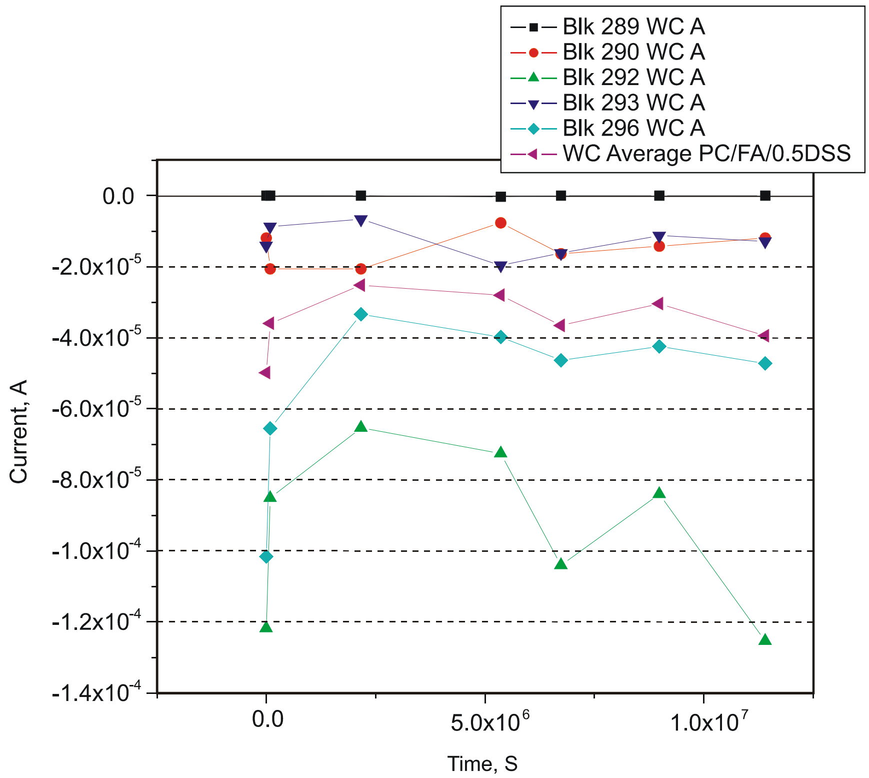


Figure 11. PC/FA/0.5DSS Cracked Specimens Demonstrated Increase in Corrosion Activity During Outside Exposure Based on Macrocell Measurements

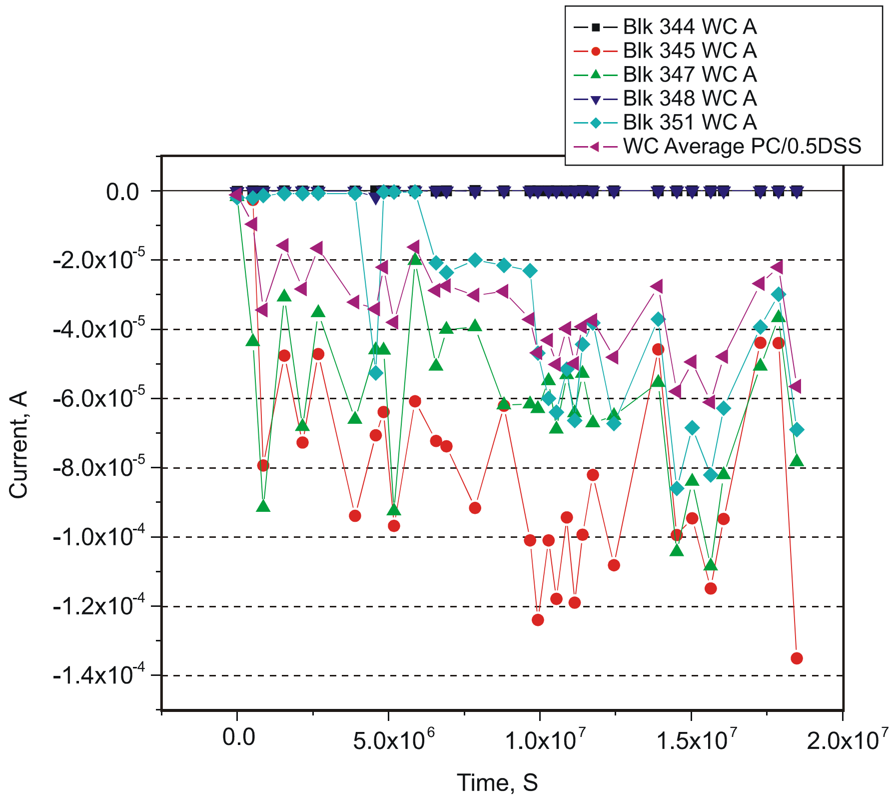


Figure 12. PC/0.5DSS Cracked Specimens Demonstrated Intermediate Good Corrosion Resistance During Laboratory Exposure Based on Macrocell Measurements

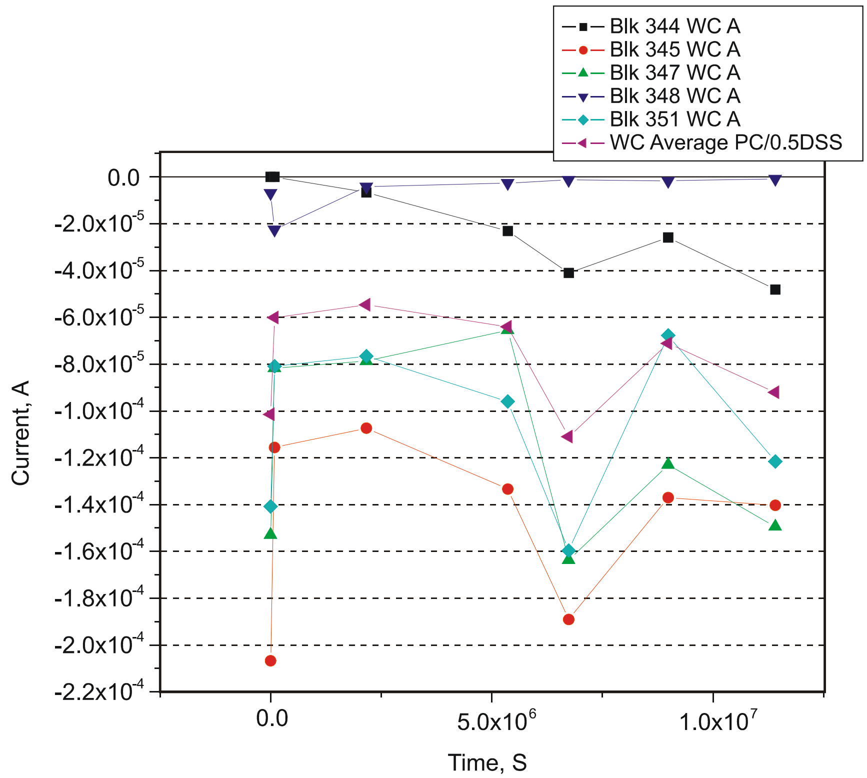


Figure 13. PC/0.5DSS Cracked Specimens Demonstrated Increase in Corrosion Activity During Outside Exposure Based on Macrocell Measurements

It was clear from the macrocell measurements shown in Figures 14 and 15 that corrosion activity in the uncracked specimens was minimal. Initially, as may be seen in Figure 14, the blocks demonstrated varying degrees of electrochemical activity between bars, but after this initial period, the activity decreased. Finally, after these uncracked specimens were moved outside, the activity between the rebar remained fairly inactive, as shown in Figure 15.

An autopsy of some of the cracked specimens indicated that corrosion was occurring. Figure 16 shows the typical exterior view of the concrete before and after testing, and Figures 17 through Figure 26 provide images of specimens after the concrete had been removed and the reinforcing steel exposed.

Chloride analysis of the uncracked specimens provided an indication of the influence of DSS on chloride diffusion into the concrete. Using the chloride analysis and exposure time, effective diffusion coefficients were calculated for each mix design studied. When DSS was admixed using 2 gal/yd^3 as opposed to 1 gal/yd^3, the average effective diffusion coefficient was lower. Further, concrete containing FA and 2 gal/yd^3 DSS had a lower average effective diffusion coefficient than concrete that contained only 1 gal/yd^3 DSS. Finally, the concrete containing portland cement, FA, and 2 gal/yd^3 DSS had the lowest average diffusion coefficient. It is important to recognize that all of the values were within a range that would be considered suitable for restricting the ingress of chlorides into the concrete. These values are presented in Figure 27.

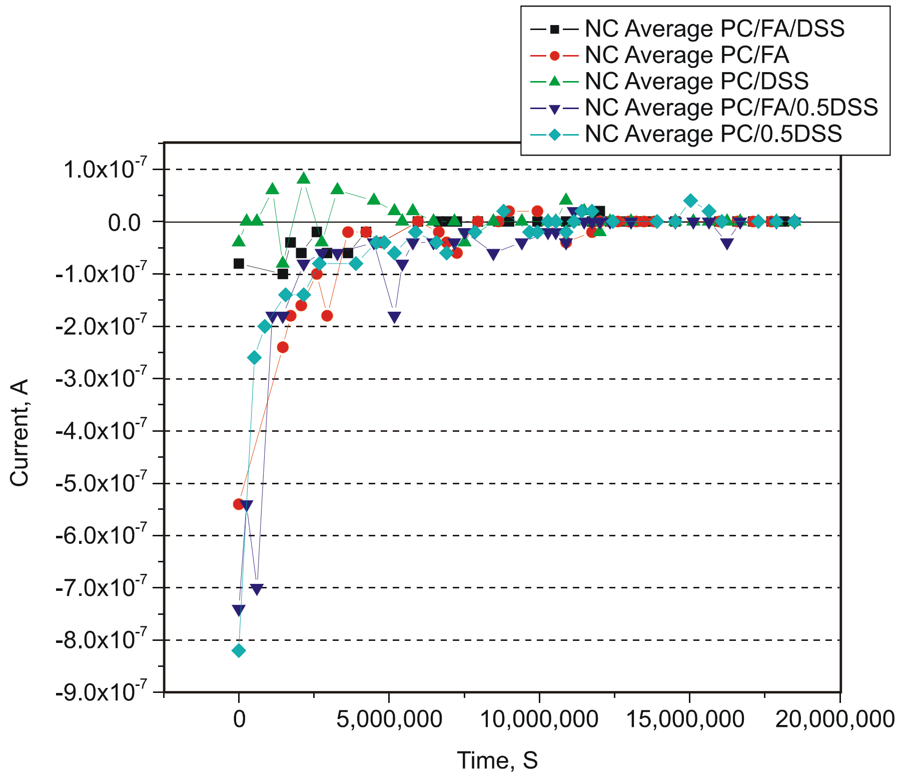


Figure 14. Average Corrosion Activity During Laboratory Exposure Based on Macrocell Measurements in Uncracked Specimens

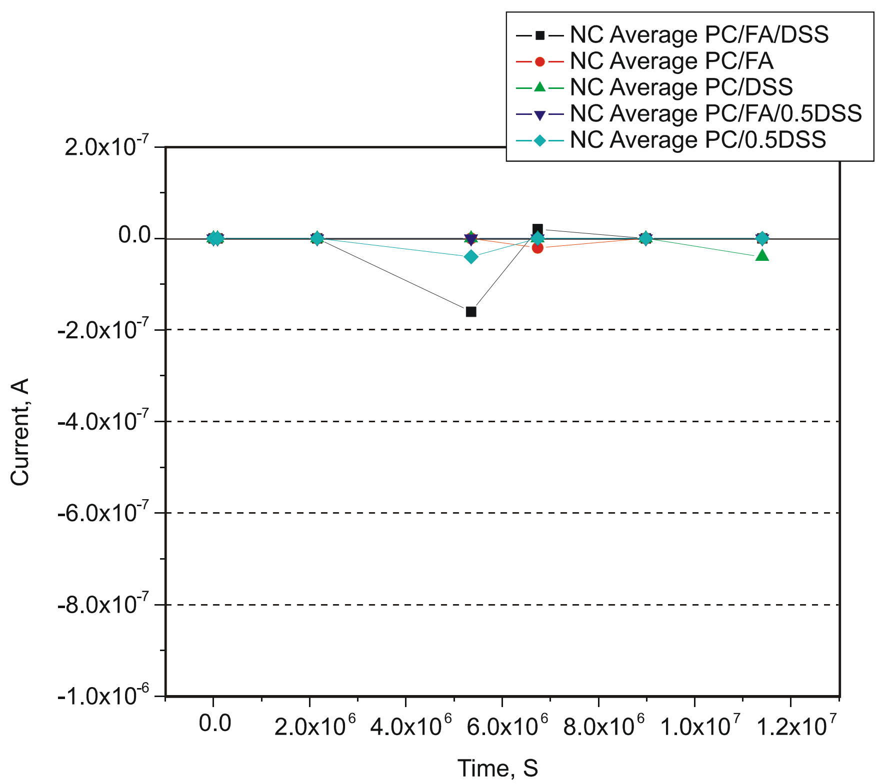


Figure 15. Average Corrosion Activity During Outdoor Exposure Based on Macrocell Measurements in Uncracked Specimens

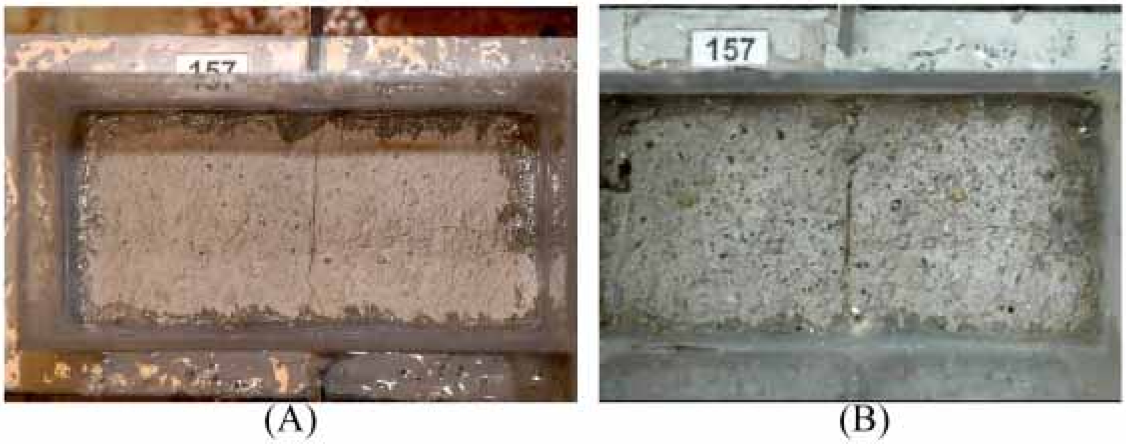


Figure 16. Typical view of specimen (A) before testing and (B) after testing, showing no outward signs of corrosion.

The sorptivity (ASTM C 1585) was lower when DSS was added, as shown in Figure 3, and the coulomb values (ASTM C 1202) were much lower when FA was added, as shown in Table 4. When evaluated in conjunction with the effective diffusion coefficients, it was not surprising that the PC/FA/DSS specimens had the lowest effective diffusion coefficient value. It is conceivable that the DSS will restrict moisture intake while the FA reduces the movement of moisture within the system: both would limit the transport of chlorides into the concrete.

Shrinkage data are also summarized in Table 4 and displayed in Figure 28. Results indicate that the PC/DSS and PC/FA specimens had the lowest shrinkage followed by the specimens from the other DSS mixtures. All values were equal or less than 400 microstrain at 28 days and less than 700 microstrain at 4 months, as recommended.[7]

Table 7 summarizes the results of the freeze-thaw testing. The acceptance criteria are weight loss of 7 and less, durability factor of 60 and more, and surface rating of 3 and less. All concretes had acceptable durability factors and surface ratings. The weight loss was above the limit in three of the batches: two with DSS and the control. However, since the durability factors are high, the surface scaling is expected to be limited only to the surface and not to progress into the concrete. Such scaling could have the beneficial effect of exposing skid-resistant aggregate.

As described previously, the resistance to ASR was tested in accordance with ASTM C 1260. This test provides a means of detecting the potential of an aggregate intended for use in concrete for undergoing ASR, resulting in potentially deleterious internal expansion. Expansions of less than 0.10 percent at 16 days after casting are indicative of innocuous behavior in most cases. In this test, mortar specimens were prepared using Type I/II PC with a reactive aggregate commercially available and used by VDOT as the control. There were three experimental mixtures: one with the inclusion of Class F FA, which reduces expansion; one with the addition of DSS to the FA mix at the recommended dosage; and one with DSS but no FA. The results displayed in Figure 29 indicate that FA reduces expansion, as expected. However, the addition of DSS had minimal effect on ASR.

The results of the bond test are summarized in Table 8. Bond strengths with and without DSS were similar, indicating that the addition of DSS does not affect bond strength.

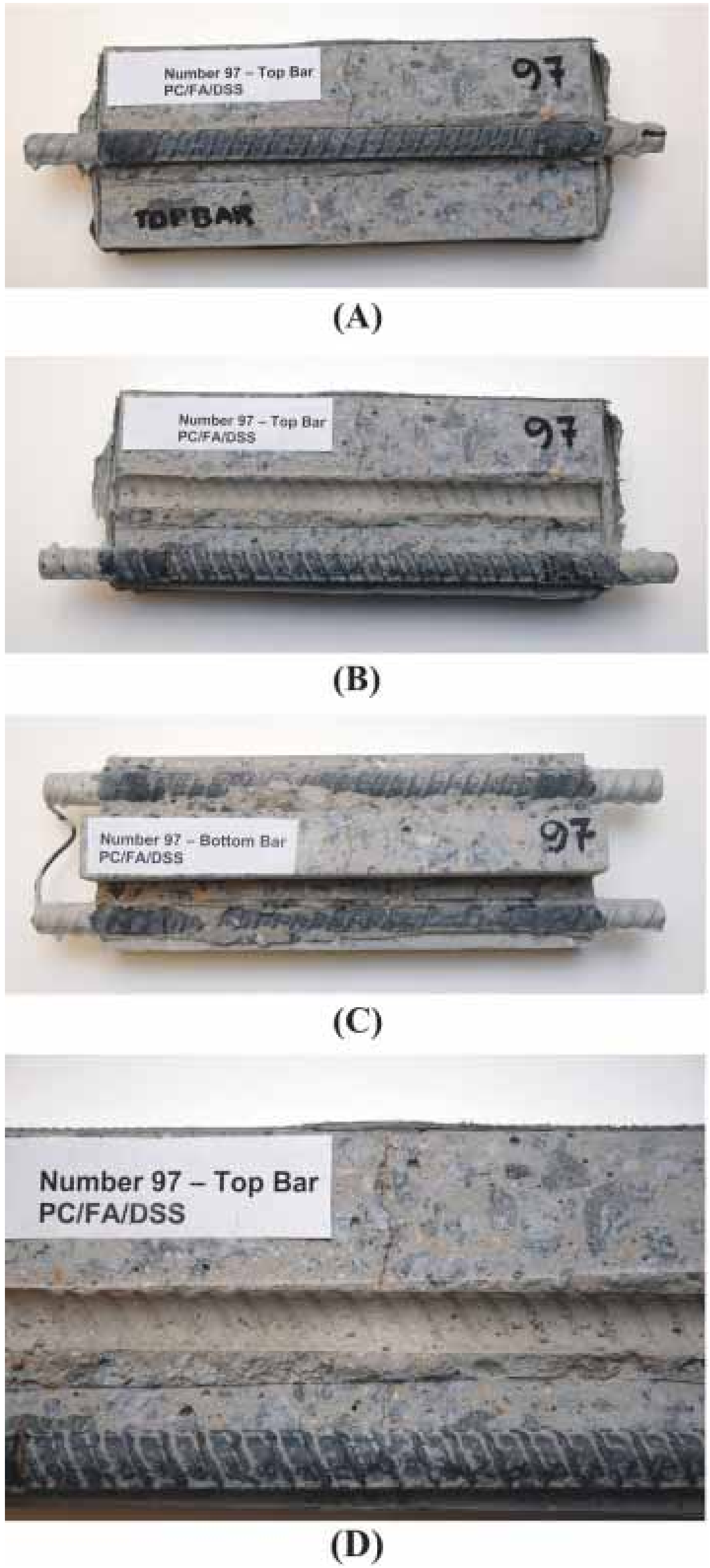


Figure 17. (A) Top bar from specimen No. 97 showing no corrosion at crack. (B) Underside of top bar shows no sign of corrosion on bottom side of rebar. (C) Two lower bars show no signs of corrosion. (D) Close-up photograph of crack. (Mix PC/FA/DSS).

(A)

(B)

(C)

(D)

Figure 18. (A) Top bar from specimen No. 98 displaying corrosion centered at crack. (B) Underside of top bar showing corrosion on bottom side of rebar but away from crack. Approximately 10% of top bar showing corrosion. (C) Two lower bars show no signs of corrosion. (D) Close-up photograph of crack. (Mix PC/FA/DSS).

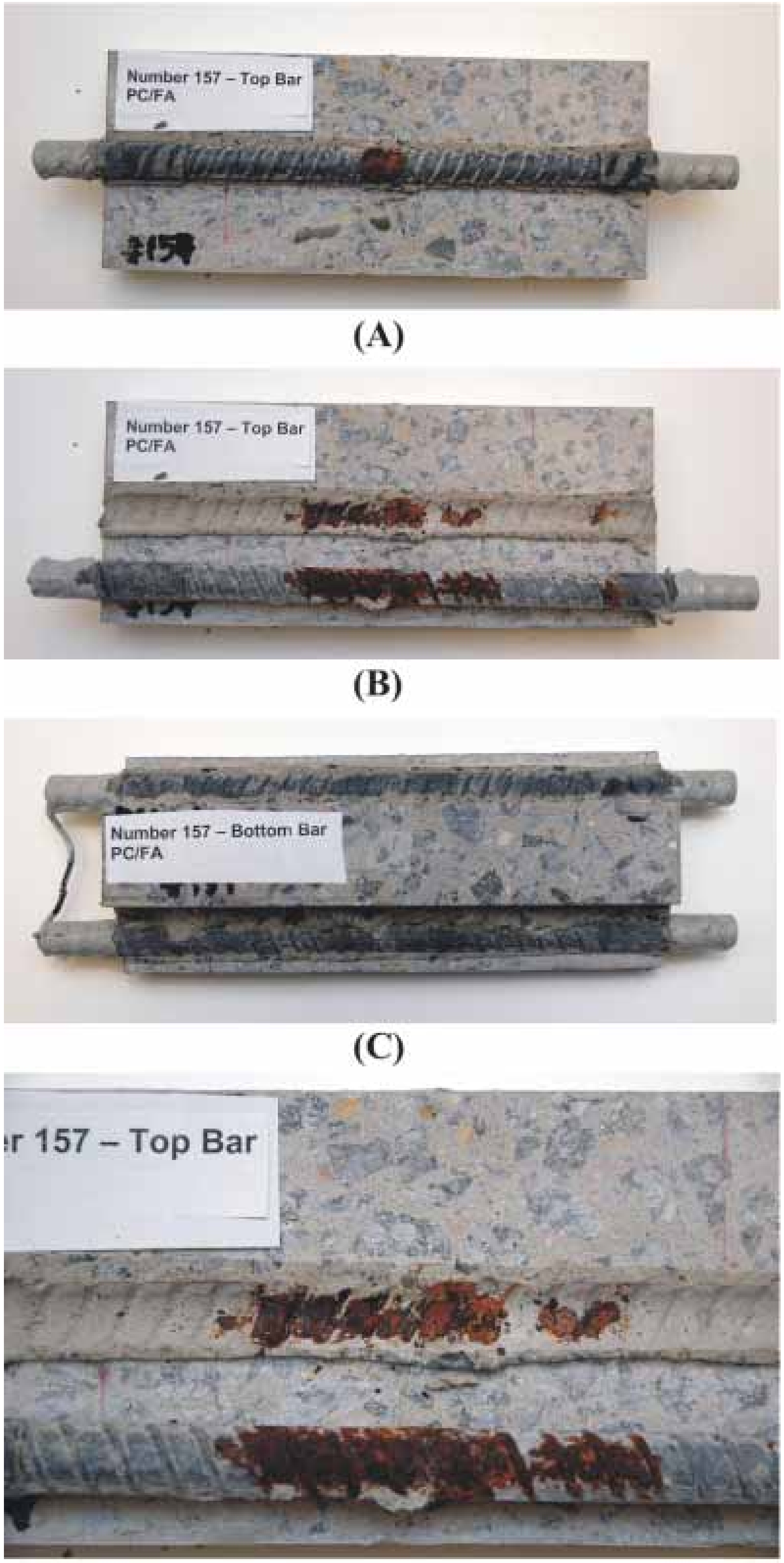
(A)

(B)

(C)

(D)

Figure 19. (A) Top bar from specimen No. 150 displaying no corrosion at crack. (B) Underside of top bar showing corrosion on bottom side of rebar. Approximately 21% of top bar showing corrosion. (C) Two lower bars showing no signs of corrosion. (D) Close-up photograph of crack. (Mix PC/FA).



(D)

Figure 20. (A) Top bar from specimen No. 157 showing corrosion centered at crack. (B) Underside of top bar showing significant corrosion on bottom side of rebar. Approximately 28% of top bar showing corrosion. (C) Two lower bars showing no signs of corrosion. (D) Close-up photograph of crack. (Mix PC/FA).

(A)

(B)

(C)

(D)

Figure 21. (A) Top bar from specimen No. 210 showing no corrosion at crack. (B) Underside of top bar showing very little corrosion on bottom side of rebar. (C) Two lower bars showing no signs of corrosion. (D) Close-up photograph of crack. (Mix PC/DSS).

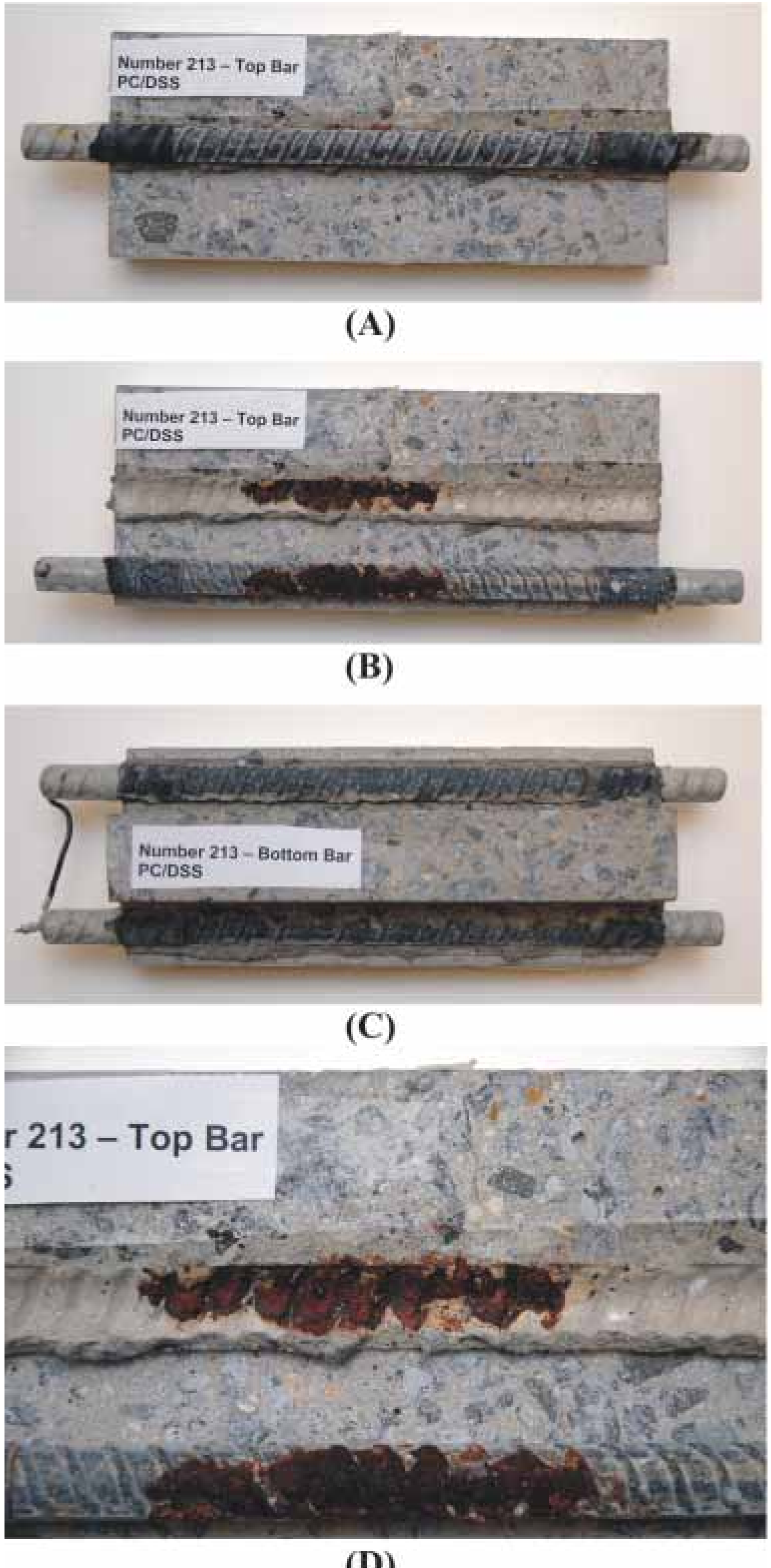


Figure 22. (A) Top bar from specimen No. 213 showing slight corrosion along bar near crack. Approximately 18% of top bar showing corrosion. (B) Underside of top bar showing corrosion on bottom side of rebar. (C) Two lower bars showing no signs of corrosion. (D) Close-up photograph of crack. (Mix PC/DSS).

(A)

(B)

(C)

(D)

Figure 23. (A) Top bar from specimen No. 289 showing no corrosion at crack. (B) Underside of top bar showing no corrosion on bottom side of rebar. (C) Two lower bars showing no sign of corrosion. (D) Close-up photograph of crack. (Mix PC/FA/0.5DSS).

(A)

(B)

(C)

(D)

Figure 24. (A) Top bar from specimen No. 292 showing corrosion centered at crack. (B) Underside of top bar showing corrosion on bottom side of rebar. Approximately 19% of top bar showing corrosion. (C) Two lower bars showing no sign of corrosion. (D) Close-up photograph of crack. (Mix PC/FA/0.5DSS).

(A)

(B)

(C)

(D)

Figure 25. (A) Top bar from specimen No. 347 showing corrosion centered at crack. (B) Underside of top bar showing corrosion on bottom side of rebar. Approximately 34% of top bar showing corrosion. (C) Two lower bars showing no sign of corrosion. (D) Close-up photograph of crack. (Mix PC/0.5DSS).

Figure 26. (A) Top bar from specimen No. 348 showing no sign of corrosion. (B) Underside of top bar showing corrosion on bottom side of rebar. Less than 1% of top bar showing corrosion. (C) Two lower bars showing no sign of corrosion. (D) Close-up photograph of crack. (Mix PC/0.5DSS).

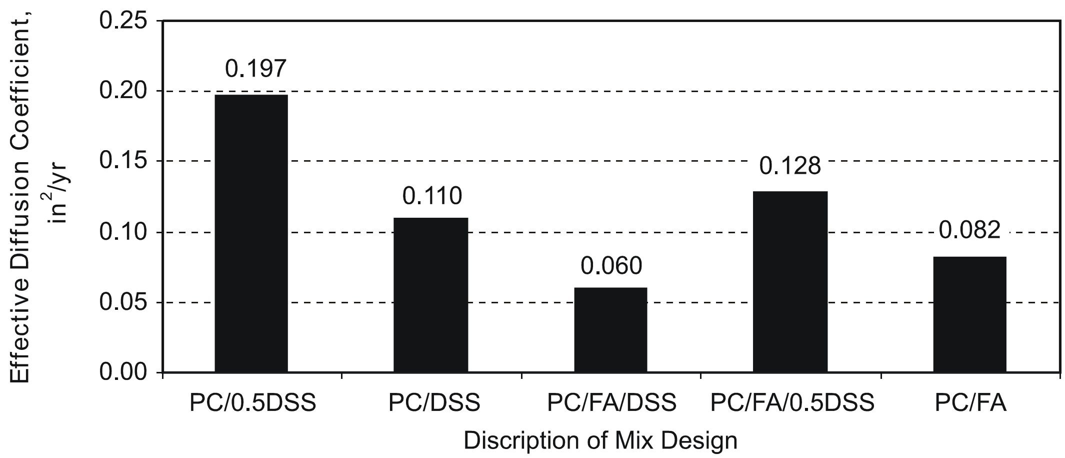


Figure 27. Effective Diffusion Coefficient for Different Mix Designs Based on Acid-Soluble Chloride Concentration Above Reinforcing Steel

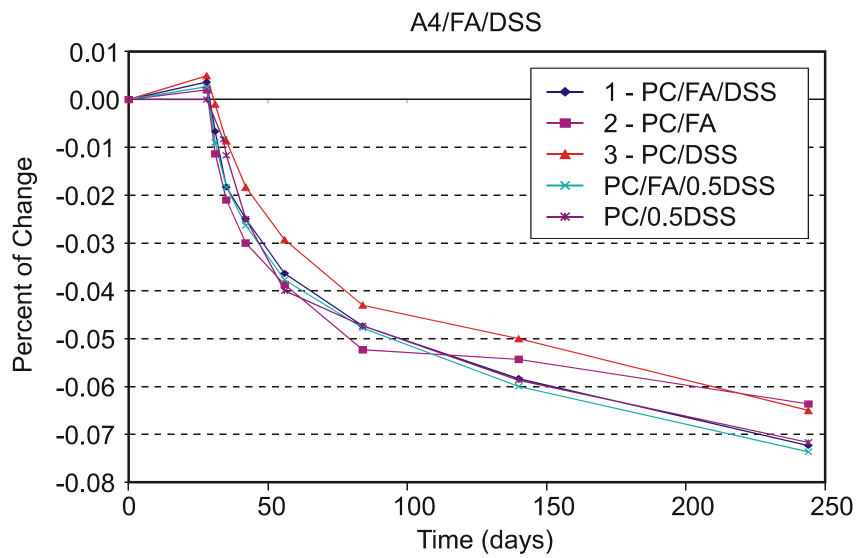


Figure 28. Shrinkage Data (ASTM C 157)

Table 7. Freeze-Thaw Resistance at 300 Cycles

Batch	Variable	Weight Loss (%)	Durability Factor	Surface Rating
B1	PC/FA/DSS	4.3	90	1.8
B2	PC/FA	8.3	94	2.6
B3	PC/DSS	7.8	87	2.4
B4	PC/FA/0.5DSS	10.5	87	2.7
B5	PC/0.5DSS	3.6	96	1.8

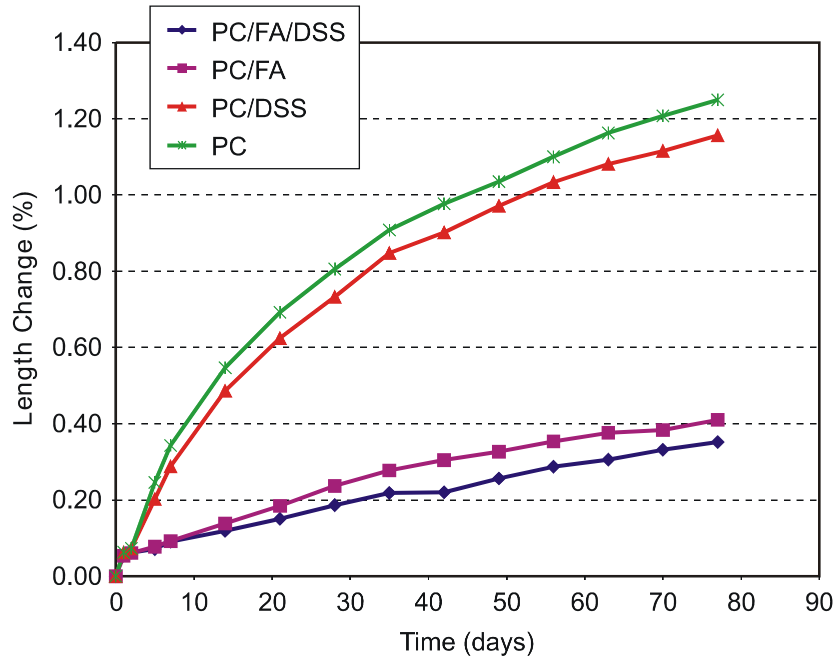


Figure 29. Length Change Due to Alkali-Silica Reactivity (ASTM C 1260)

Table 8. Tensile Bond Strength Data

Material	**Sample No.**	**Bond Strength (psi)**	**Failure Area (%)**		
			Overlay	**Bond**	**Base**
PC/FA	1	257	100	0	0
	2	221	60	40	0
	3	341	100	0	0
	4	132	40	60	0
	Average	238			
	Std. Dev.	87			
PC/FA/DSS	5	341	20	80	0
	6	203	100	0	0
	7	293	100	0	0
	8	167	0	100	0
	Average	251			
	Std. Dev.	80			

SUMMARY OF FINDINGS

- Hycrete DSS with a defoaming agent achieved air contents within VDOT's specifications.
- With the required air contents, concretes with and without Hycrete DSS had high durability factors even though some of the specimens had high weight loss. Because of the high durability factors, the high weight loss is not expected to be a problem considering the severity of the test.
- Long-term strengths were similar for concretes with similar air contents.

- The rapid chloride permeability test did not show any benefit of adding Hycrete DSS. The addition of Class F fly ash did result in low permeability. However, sorptivity was lower when the Hycrete DSS was added.

- The DSS will restrict moisture intake while the fly ash reduces the movement of moisture within the system, which restricts the chlorides movement into the concrete. This is based on the data from the rapid chloride permeability and rate of absorption tests in conjunction with the effective diffusion coefficients information calculations.

- The drying shrinkage values were acceptable for all mixtures tested.

- The bond strength values were similar for all mixtures tested. Thus, Hycrete DSS had no effect on the bond to concrete.

- The addition of fly ash improved the resistance to ASR, whereas the addition of Hycrete DSS did not.

- Outdoor exposure strongly affected the amount of charge passed in the cracked specimens, increasing the activity of those specimens that had minimal activity in the laboratory, which indicates Hycrete DSS might be affected by the environmental influences that are found outdoors.

- When cracks in concrete intersected the reinforcing steel, Hycrete DSS did not prevent the initiation of corrosion.

CONCLUSIONS

- VDOT's Class A4 concrete mix benefits from the addition of fly ash.

- The addition of a sufficient amount of Hycrete DSS to a mix containing fly ash can improve the Class A4 mix by further reducing the influx of chloride ions toward the reinforcing steel.

- It is important that Hycrete DSS not be used as a replacement for fly ash in the Class A4 mix.

RECOMMENDATIONS

1. VDOT's Structure & Bridge Division should continue the use of pozzolans in order to reduce the influx of chloride ions toward the reinforcing steel and increase the life of the structure.

2. VDOT's Structure & Bridge Division should make a trial batch of Class A4 concrete with pozzolons and Hycrete DSS for placement in a bridge deck to evaluate its performance in the field.

COSTS AND BENEFITS ASSESSMENT

In assessing the cost-effectiveness of using Hycrete DSS, its up-front material cost must be weighed against the benefit of enhanced corrosion resistance, which will be associated with cost savings accrued over the life of the structure. The premium paid when Hycrete DSS is added to a Class A4 concrete mixture may range from 25 to 30 percent of the cost per cubic yard. However, this increase is less than 10 percent, considering the per cubic yard cost for in-place concrete. In the total cost of the bridge, the increase is much smaller, within a few percentage points. Therefore, if the field performance confirms the laboratory test results of this study, the use of Hycrete DSS is expected to lead to extended service life and to aid in minimizing maintenance costs.

VDOT will spend approximately $15 million for new bridge decks this construction season. Based on a life cycle cost analysis, with a 10 percent increase in the service life of bridge decks or structures, VDOT would save $1.5 million dollars each year through the use of Hycrete DSS.

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