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# Corrosion Sensitivity of Concrete Mix Designs

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Final Report VCTIR 14-R19

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**www.VTRC.net**

## Standard Title Page - Report on Federally Funded Project

| | | |
|---|---|---|
| 1. Report No.:<br>FHWA/VCTIR 14-R19 | 2. Government Accession No.: | 3. Recipient's Catalog No.: |
| 4. Title and Subtitle:<br>Corrosion Sensitivity of Concrete Mix Designs | | 5. Report Date:<br>June 2014 |
| | | 6. Performing Organization Code: |
| 7. Author(s):<br>Stephen R. Sharp, Ph.D., P.E., Celik Ozyildirim, Ph.D., P.E., and David W. Mokarem, Ph.D. | | 8. Performing Organization Report No.:<br>VCTIR 14-R19 |
| 9. Performing Organization and Address:<br>Virginia Center for Transportation Innovation and Research<br>530 Edgemont Road<br>Charlottesville, VA 22903 | | 10. Work Unit No. (TRAIS): |
| | | 11. Contract or Grant No.:<br>99206 |
| 12. Sponsoring Agencies' Name and Address:<br>Virginia Department of Transportation<br>1401 E. Broad Street<br>Richmond, VA 23219 | Federal Highway Administration<br>400 North 8th Street, Room 750<br>Richmond, VA 23219-4825 | 13. Type of Report and Period Covered:<br>Final |
| | | 14. Sponsoring Agency Code: |
| 15. Supplementary Notes: | | |

16. Abstract:

This study compared the durability of concrete mixtures containing supplementary cementitious materials (SCMs) by evaluating the permeability, absorption, and corrosion resistance of seven mix designs and two types of reinforcement.

Permeability and alkalinity are contributing factors to the durability of portland cement concrete and can strongly influence the service life and corrosion resistance of the embedded steel. In reinforced concrete systems, the ingress of chloride ions increases the probability of corrosion of the reinforcing steel. Reducing the permeability of concrete enhances its durability by hindering the ingress of chloride ions from reaching the embedded steel surface and initiating corrosion. SCMs such as Class F fly ash, silica fume, and slag cement are widely used in concrete in an effort to reduce permeability. In addition, the alkaline environment of concrete enables the formation of a passive film on the surface of the steel. As long as this protective environment is maintained, the corrosion rate of the reinforcing bar will be insignificant for the majority of applications.

The results of this study indicated that the use of SCMs can reduce the permeability and absorption of the concrete, leading to more durable structures than those with plain concretes; therefore, their continued use in structures by the Virginia Department of Transportation is recommended. However, different SCMs have varying levels of durability, and the agency should consider this information when selecting SCMs for specific applications.

The absorption test results in this study provided a reasonable correlation with the corrosion test results. Therefore, the absorption test should be more closely investigated as a means of evaluating the corrosion protection provided by SCMs. This study also demonstrated that the corrosion-resistant reinforcement plays the most vital role in minimizing corrosion. SCMs provide durable concretes and in combination with the corrosion-resistant reinforcement ensure reinforced concrete structures with longer service lives.

| | | | |
|---|---|---|---|
| 17 Key Words:<br>Concrete, supplementary cementitious materials, corrosion, permeability, durability, absorption | | 18. Distribution Statement:<br>No restrictions. This document is available to the public through NTIS, Springfield, VA 22161. | |
| 19. Security Classif. (of this report):<br>Unclassified | 20. Security Classif. (of this page):<br>Unclassified | 21. No. of Pages:<br>30 | 22. Price: |

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In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Center for Transportation Innovation and Research
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

June 2014
VCTIR 14-R19

# DISCLAIMER

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## INTRODUCTION

Permeability and alkalinity are contributing factors to the durability of portland cement concrete. Permeability is a measure of the ability of substances, such as water or ions, to migrate throughout the concrete. In the case of reinforced concrete systems, the ingress of chloride ions increases the probability of corrosion of the reinforcing steel. A less permeable concrete will enhance its durability by hindering the penetration of chloride ions into the embedded steel surface where corrosion would be initiated. The use of pozzolans, such as Class F fly ash or silica fume, and slag cement with portland cement usually helps in creating a less permeable system, thus reducing the ability of aggressive ions to migrate to the steel surface. These materials are known as supplementary cementitious materials (SCMs). Although SCMS are used to reduce permeability, their effect on the chloride diffusion coefficients can vary for different mix designs (Lane, 2010). Lane (2010) showed that concretes containing slag cement have a lower diffusion coefficient than those with Class F fly ash.

When steel is embedded in concrete, the highly alkaline environment thermodynamically favors the formation of a passive film on the surface of the steel. As long as this protective environment is maintained, the corrosion rate of the reinforcing bar (rebar) becomes insignificant. However, if the pH adjacent to the steel drops and/or if the chloride concentration at the steel substantially increases, the effect of this passive film is lessened and the steel is more susceptible to the initiation of corrosion. Therefore, the corrosion susceptibility of the embedded reinforcing steel is strongly dependent on the concentration of chloride ions and the pH of the concrete at the depth of the steel. This relationship between the chloride and alkalinity concentrations is shown in Equation 1. Hausmann (1967) concluded that the chloride threshold value should not exceed 0.61.

$$\frac{[Cl^-]}{[OH^-]} \le 0.61 \qquad \text{[Eq. 1]}$$

From Equation 1 it is evident that a drop in the alkalinity increases the chances of corrosion by reducing the chloride concentration required to initiate corrosion. In general, there have been many studies investigating the effect of pozzolans and slag cement on the alkalinity of the concrete and it is accepted that the alkalinity may be reduced, but in most cases it is believed that the permeability is reduced enough to minimize the diffusion of chlorides to the steel and offset the effects of lowered alkalinity. This raises an issue because although the chloride ion is focused on in numerous studies, the influence of the alkalinity should not be underestimated when a corrosion-resistant structure is designed. Recently it was suggested that the resistance of the structure to corrosion could be improved by electrochemically treating a structure and increasing the alkalinity before chloride ions were able to initiate corrosion. Glass and Buenfeld (2000) presented this idea. Based on this idea, rather than reducing the chloride concentration, the concentration of hydroxide ions is increased, which therefore increases the chloride threshold, as shown in Equation 1.

The durability of the reinforced concrete system depends on many factors. Understanding individual factors such as permeability and absorption and how they affect each other is critical for a full comprehension of the durability of an entire system.

Another important factor in corrosion resistance of reinforced concrete is the selection of the reinforcement. The Virginia Department of Transportation (VDOT) no longer uses epoxy-coated reinforcement in new bridge decks and has replaced it with corrosion-resistant reinforcement (CRR) (VDOT, 2012). Depending on the type of CRR selected, varying levels of corrosion protection are provided. For example, a certain type of stainless steel can provide more protection than other types of stainless steel in a given environment (Hartt et al., 2007; Presuel-Moreno et al., 2008).

## PURPOSE AND SCOPE

The purpose of this study was to assess the influence of the alkalinity and permeability of seven different concrete mixtures on the corrosion resistance of the embedded steel when the concrete is subjected to saltwater. It is known that the alkalinity and permeability of concrete can influence the time to corrosion of the embedded steel. Therefore, by better understanding the characteristics of absorption and permeability, VDOT can select optimized mixtures for a variety of applications.

This study was performed with laboratory samples of concrete that were mixed by one of two entities: (1) a Virginia ready-mixed concrete producer, and (2) the Virginia Center for Transportation Innovation and Research (VCTIR). The ready-mixed concrete samples were cast first and provided insight into the behavior of the field mixtures. Subsequently, mixtures were cast at the VCTIR laboratory in a more controlled environment. The VCTIR mixtures were used to understand better the behavior of each mixture when it was subjected to more favorable casting and curing conditions than were the case with the ready-mixed concretes.

The concrete mixtures contained pozzolans, Class F fly ash and silica fume, and slag cement in routine VDOT binary systems or in novel ternary systems. In addition to the properties of fresh and hardened concretes, specimens with black steel reinforcement or corrosion-resistant reinforcing steel conforming to the requirements of ASTM A1035 (hereinafter ASTM A1035 steel) (ASTM, 2004) were prepared to assess the response to saltwater exposure and the ensuing corrosion of the embedded steel.

# METHODS

## Overview

The evaluation involved the following:

1. *The casting of seven different concrete mixtures that were produced by a Virginia ready-mixed concrete producer in 2007 (hereinafter ready-mixed).* The reason these mixtures were produced was so that the behavior of concretes prepared in a ready-mixed concrete truck for field delivery could be better understood. Measurements were made on fresh and hardened concrete samples collected outside the laboratory from the truck mixer. This portion of the study was concluded after the corrosion test samples were autopsied and the amount of corrosion damage was visually determined.

2. *The casting of seven different concrete mixtures that were made in the VCTIR laboratory in 2009 (hereinafter VCTIR).* The reason these mixtures were produced was so that they could be compared with the concretes from the truck mixer to determine the effect of more efficient casting and better controlled curing conditions. Measurements were made on fresh and hardened concrete mixed in the laboratory pan mixer. This portion of the study was concluded after the corrosion test samples were autopsied and the amount of corrosion damage was visually determined.

The following sections describe the concrete mixture designs; the ready-mixed and VCTIR fresh and hardened concrete tests; and the corrosion testing of tombstone samples.

## Concrete Mix Designs

The mixtures in this study all contained Type II cement, natural sand, crushed stone coarse aggregate, and various admixtures as needed. The control mixture was plain concrete with no SCMs. In the other mixtures, a single pozzolanic material (binary) or two pozzolanic materials (ternary) were used with the portland cement as shown in Tables 1 through 7. The ready-mixed concrete mixture had a total cementitious material content 6% higher than that of the VCTIR mixtures, but the water–cementitious material ratio (w/cm) was the same at 0.45.

**Table 1. Mixture Proportions for Control Mixtures (100% PC)**

| Ingredient | Ready-Mixed (lb/yd$^3$) | VCTIR (lb/yd$^3$) |
|---|---|---|
| Type II cement | 675 | 635 |
| Fine aggregate | 1167 | 1037 |
| Coarse aggregate | 1781 | 1823 |
| Water | 300 | 286 |
| Maximum w/cm | .45 | .45 |

PC = portland cement; w/cm = water–cementitious material ratio.

**Table 2. Mixture Proportions for 20% Fly Ash Mixtures (80% PC + 20% FA)**

| Ingredient | Ready-Mixed (lb/yd$^3$) | VCTIR (lb/yd$^3$) |
|---|---|---|
| Type II cement | 540 | 508 |
| Fly ash | 135 | 127 |
| Fine aggregate | 1,101 | 997 |
| Coarse aggregate | 1,781 | 1,823 |
| Water | 300 | 286 |
| Maximum w/cm | 0.45 | 0.45 |

PC = portland cement; FA = fly ash; w/cm = water–cementitious material ratio.

**Table 3. Mixture Proportions for 40% Slag Cement Mixtures (60% PC + 40% Slag)**

| Ingredient | Ready-Mixed (lb/yd$^3$) | VCTIR (lb/yd$^3$) |
|---|---|---|
| Type II cement | 405 | 381 |
| Slag | 270 | 254 |
| Fine aggregate | 1,150 | 1,022 |
| Coarse aggregate | 1,781 | 1,823 |
| Water | 300 | 286 |
| Maximum w/cm | .45 | .45 |

PC = portland cement; w/cm = water–cementitious material ratio.

**Table 4. Mixture Proportions for 7% Silica Fume Mixtures (93% PC + 7% SF)**

| Ingredient | Ready-Mixed (lb/yd$^3$) | VCTIR (lb/yd$^3$) |
|---|---|---|
| Type II cement | 625 | 591 |
| Silica fume | 50 | 44 |
| Fine aggregate | 1,149 | 1,022 |
| Coarse aggregate | 1,781 | 1,823 |
| Water | 300 | 286 |
| Maximum w/cm | .45 | .45 |

PC = portland cement; SF = silica fume; w/cm = water–cementitious material ratio.

**Table 5. Mixture Proportions for Ternary Mixtures With 25% Slag and 2.5% Silica Fume (72.5% PC + 25% Slag + 2.5% SF)**

| Ingredient | Ready-Mixed (lb/yd$^3$) | VCTIR (lb/yd$^3$) |
|---|---|---|
| Type II cement | 489 | 460 |
| Slag | 169 | 159 |
| Silica fume | 17 | 16 |
| Fine aggregate | 1150 | 1022 |
| Coarse aggregate | 1781 | 1823 |
| Water | 300 | 286 |
| Maximum w/cm | .45 | .45 |

PC = portland cement; w/cm = water–cementitious material ratio.

**Table 6. Mixture Proportions for Ternary Mixtures With 15% Fly Ash and 2.5% Silica Fume (82.5% PC + 15% FA + 2.5% SF)**

| Ingredient | Ready-Mixed (lb/yd$^3$) | VCTIR (lb/yd$^3$) |
|---|---|---|
| Type II cement | 557 | 524 |
| Fly ash | 101 | 95 |
| Silica fume | 17 | 16 |
| Fine aggregate | 1129 | 1001 |
| Coarse aggregate | 1781 | 1823 |
| Water | 300 | 286 |
| Maximum w/cm | .45 | .45 |

PC = portland cement; FA = fly ash; SF = silica fume; w/cm = water–cementitious material ratio.

**Table 7. Mixture Proportions for Ternary Mixtures With 25% Fly Ash and 25% Slag (50% PC + 25% FA + 25% Slag)**

| Ingredient | Ready-Mixed (lb/yd$^3$) | VCTIR (lb/yd$^3$) |
|---|---|---|
| Type II cement | 337 | 317 |
| Slag | 169 | 159 |
| Fly ash | 169 | 159 |
| Fine aggregate | 1103 | 976 |
| Coarse aggregate | 1781 | 1823 |
| Water | 300 | 286 |
| Maximum w/cm | .45 | .45 |

PC = portland cement; FA = fly ash; w/cm = water–cementitious material ratio.

## Concrete Tests

Both the ready-mixed and VCTIR mixtures were tested at the fresh state as indicated in Table 8. The hardened concrete specimens were subjected to the tests listed in Table 9. When applicable, the results from the tests listed in Tables 8 and 9 were compared to the VDOT specification values provided in Table 10.

**Table 8. Fresh Concrete Tests**

| Test | Specification |
|---|---|
| Slump | ASTM C143 (ASTM, 2012b) |
| Air content | ASTM C173 (ASTM, 2012c) |
| Temperature | ASTM C1064 (ASTM, 2012d) |
| Unit weight (density) | ASTM C138 (ASTM, 2013a) |

**Table 9. Hardened Concrete Tests**

| Test | Specification | Size (in) |
|---|---|---|
| Compressive strength | ASTM C39 (ASTM, 2012a) | 4 x 8 |
| Elastic modulus | ASTM C469 (ASTM, 2010) | 4 x 8 |
| Permeability | ASTM 1202 (ASTM, 2012e) | 2 x 4 |
| Absorption rate | ASTM C1585 (ASTM, 2013b) | 2 x 4 |

Specimens tested for permeability were moist cured for 7 days at room temperature and then for 3 weeks at 100 °F. Tests for absorption rate were conducted 1 year after casting.

**Table 10. VDOT Specifications for A4 Concrete**

| Property | Value |
|---|---|
| Minimum compressive strength (psi) | 4,000 |
| Nominal maximum aggregate size (in) | 1 |
| Minimum cement content (lb/yd$^3$) | 635 |
| Maximum w/cm | 0.45 |
| Slump (in) | 6.5 ± 1.5 |
| Air content (%) | 6.5 ± 1.5 |

*Source:* Virginia Department of Transportation, *Road and Bridge Specifications,* Richmond, 2007. w/cm = water–cementitious material ratio. When a high-range water reducing admixture is used, the upper limit for entrained air may be increased by 1% and the slump must not exceed 7 in.

## Corrosion Testing of Tombstone Samples

For corrosion testing, two types of reinforcement were selected: (1) ASTM A1035 steel was selected because VDOT uses this type of reinforcement in its structures (ASTM, 2004), and (2) carbon steel rebar was selected because it has been widely used and historical data are available. Therefore, rebar was used as a baseline to enable comparisons with other corrosion studies.

The design of the specimens and procedures followed for this test were previously described by Sharp et al. (2011). The specimens were exposed to saltwater using a cyclical ponding routine of 3 days wet followed by 4 days dry.

# RESULTS AND DISCUSSION

## Ready-Mix Concrete

### Ready-Mix Concrete Tests

The results of the fresh concrete tests (Table 11) indicated workable concretes with slump values ranging from 2.0 to 7.8 in and air contents ranging from 5.3% to 8.5%. The slump values exceeded the VDOT specifications in three batches, but they were all stable mixtures. The air contents were within the specification for all ready-mixed batches. Weather conditions during the placement were favorable, with air temperatures staying below 80 °F and humidity varying from 45% to 77%.

**Table 11. Fresh Concrete Properties for Ready-Mixed Concrete**

| **Date** | 5/14/07 | 5/22/07 | 5/29/07 | 6/4/07 | 6/18/07 | 6/26/07 | 7/2/07 |
|---|---|---|---|---|---|---|---|
| **Mixture (%)** | 80 PC + 20 FA | 60 PC + 40 Slag | 100 PC | 93 PC + 7 SF | 72.5 PC + 25 Slag + 2.5 SF | 82.5 PC + 15 FA + 2.5 SF | 50 PC + 25 FA + 25 Slag |
| **Slump (in)** | 2.8 | 2.5 | 3.2 | 7.8 | 2.0 | 7.5 | 7.5 |
| **Air content (%)** | 5.3 | 5.4 | 7.0 | 6.0 | 8.5 | 6.1 | 6.0 |
| **Concrete temperature (°F)** | 69 | 74 | 78 | 80 | 98 | 84 | 79 |
| **Air temperature (°F)** | 62 | 66 | 73 | 71 | 76 | 80 | 65 |
| **Relative humidity (%)** | 45 | 76 | 58 | 64 | 77 | 66 | 54 |
| **Density (lb/ft$^3$)** | 146.0 | 147.2 | 144.0 | 144.8 | 146.4 | 143.6 | 145.2 |

PC = portland cement; FA = fly ash; SF = silica fume.

The compressive strength data are given in Figure 1. All 7-day strengths exceeded 2,000 psi, 2-day strengths exceeded 3,500 psi, and 365-day strengths exceeded 5,000 psi, as shown in Figure 1. Three of the mixtures (93% PC + 7% SF; 82.5% PC + 15% FA + 2.5% SF; and 50% PC + 25% FA + 25% Slag) achieved a lower 7-day compressive strength than the control mixture but reached a relatively similar high strength at 1 year. Similar trends are also shown in the elastic modulus data in Figure 2 and the splitting tensile strength data in Figure 3.

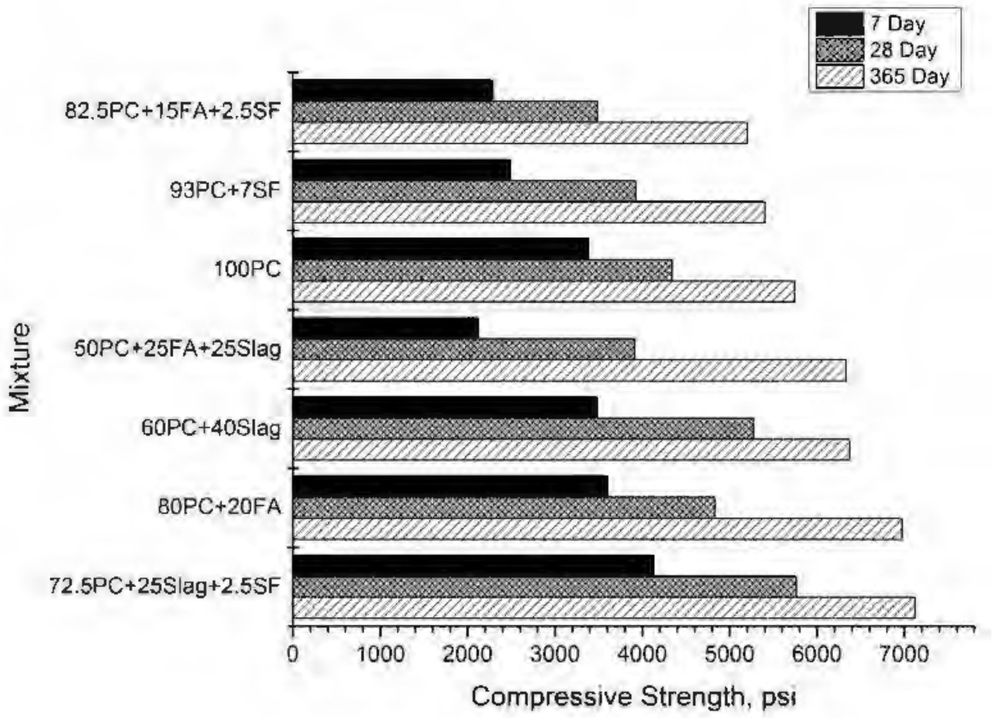

**Figure 1. Compressive Strength Data for Ready-Mixed Concrete Mixtures**

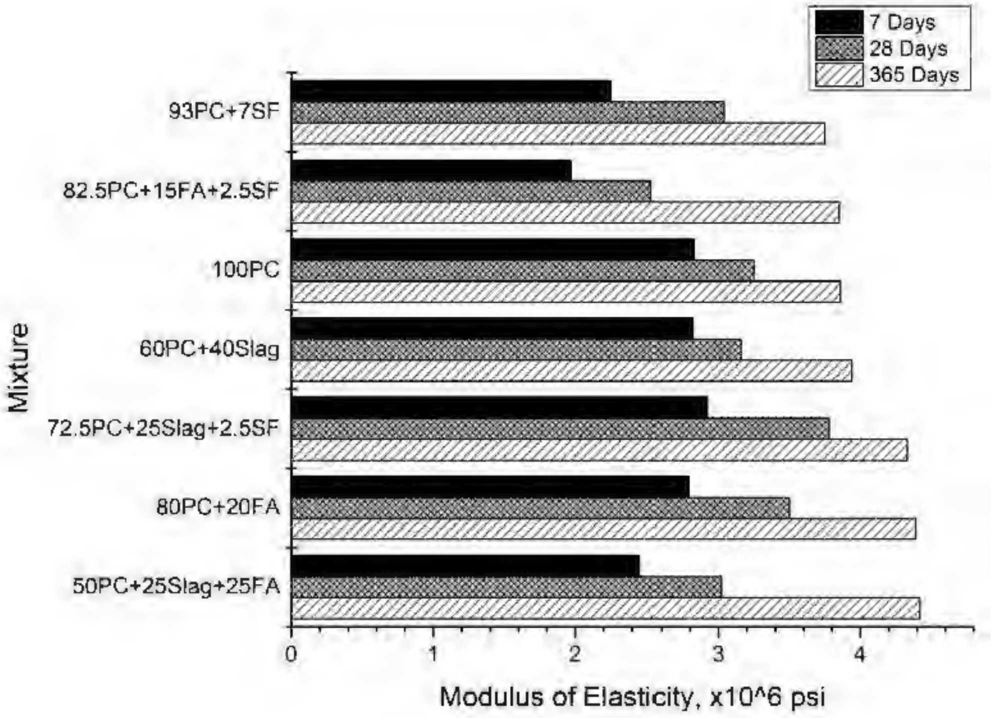

Figure 2. Modulus of Elasticity Data for Ready-Mixed Concrete Mixtures

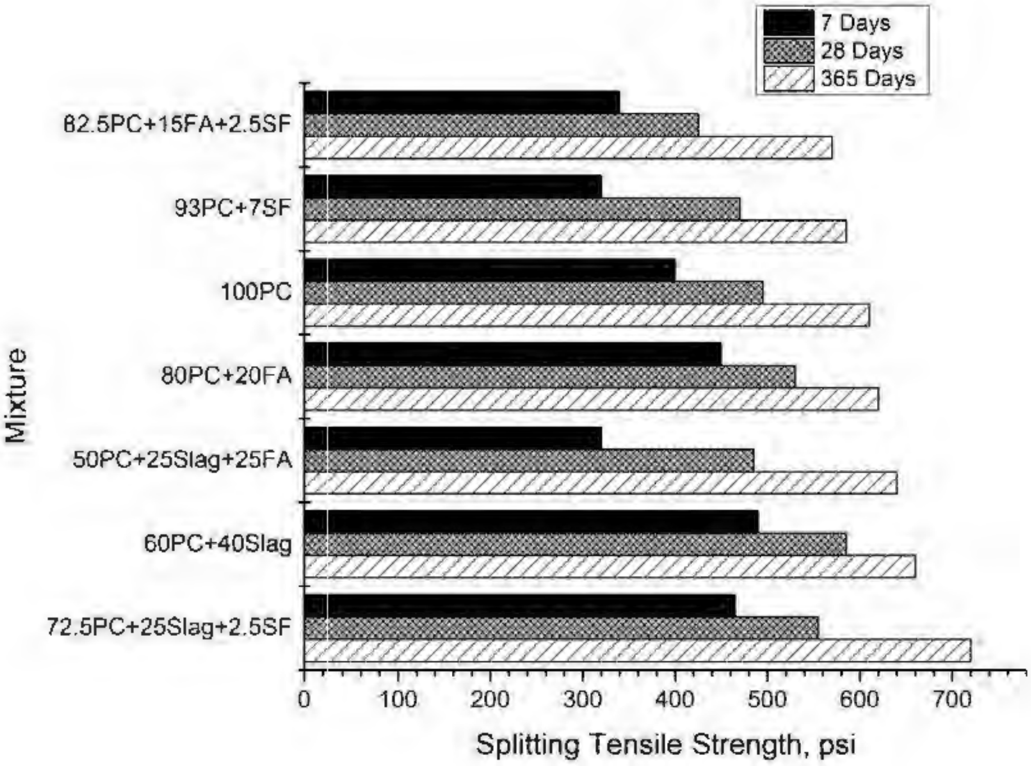

Figure 3. Splitting Tensile Strength Data for Ready-Mixed Concrete Mixtures

The permeability results displayed in Figure 4 show that the addition of SCMs such as fly ash, slag cement, and silica fume, in various percentages, will lead to reduced permeability as compared to the control. The lowest permeability values were for 60% PC + 40% Slag, 50% PC + 25% Slag + 25% FA, and 72.5% PC + 25% Slag + 2.5% SF, all containing slag cement. Capillary absorption data given in Figure 5 also showed that these three mixtures had the lowest absorption. The silica fume mixture had a lower permeability response when compared to the fly ash mixture, although the opposite behavior was observed in the capillary absorption results.

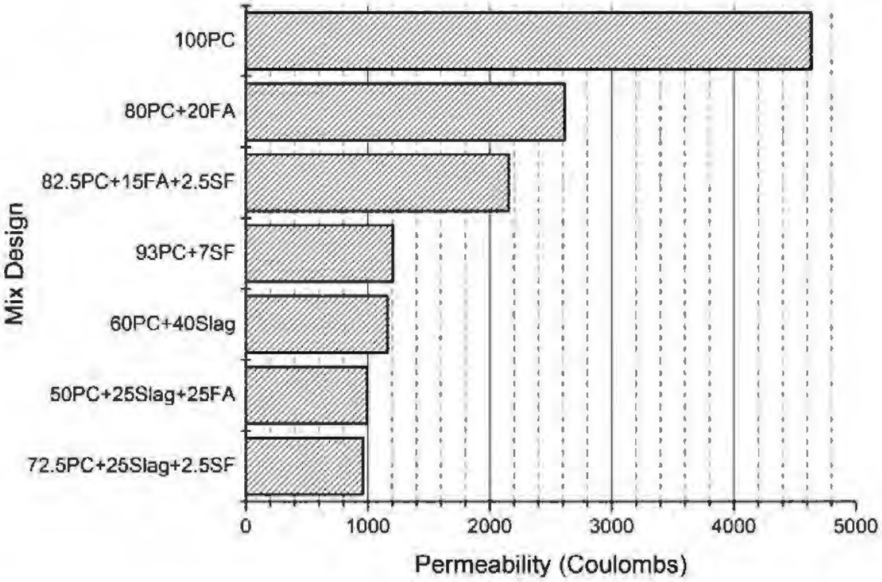

**Figure 4. Permeability Data for Ready-Mixed Concrete Mixtures**

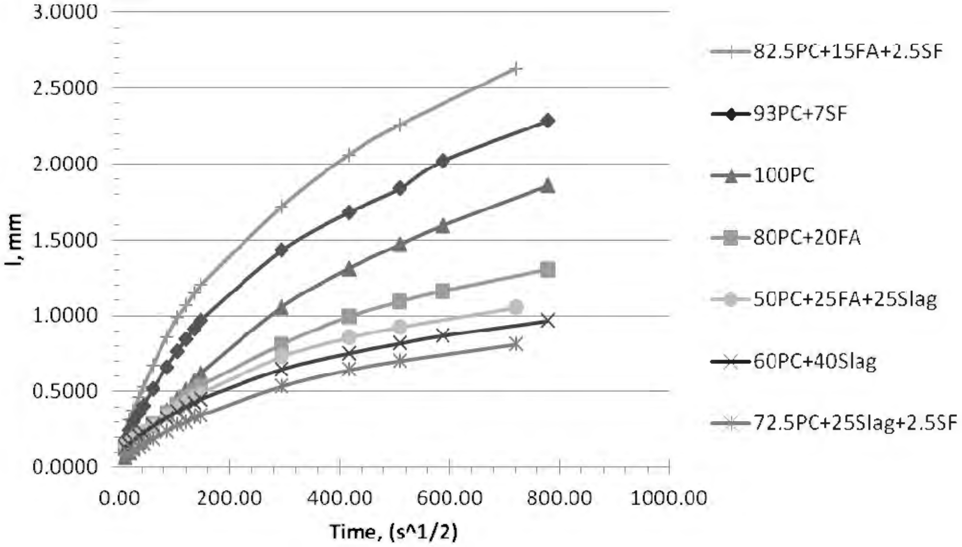

**Figure 5. Capillary Absorption Data for Ready-Mixed Concrete Mixtures**

## Ready-Mixed Corrosion Testing

The results of the tombstone test are summarized in Table 12 and displayed in Figures 6 through 12. When concrete was ranked on its ability to minimize corrosion of the same type of reinforcing steel, ASTM A1035 steel in this case, clearly the 60% PC + 40% Slag samples corroded the least and the 93% PC + 7% SF samples corroded the most. This raises questions on the quality of the concretes containing silica fume produced in the truck mixers. Silica fume increases the water demand, and if this is met with additional water, overall quality is reduced. The results indicate how different SCMs can result in different levels of corrosion protection for the embedded reinforcing steel.

It was also evident that of all the tested batches containing SCMs, the 80% PC + 20% FA samples corroded the most of all ready-mixed concrete samples. This was expected since these samples were the only ones using carbon steel rebar, which has minimal inherent corrosion resistance as compared to ASTM A1035 steel. This helps demonstrate the importance of using CRR.

It is even more interesting if the permeability results (Figure 4), the capillary absorption results (Figure 5), and the resulting corrosion area (Table 12) are compared. In general, the corrosion area rankings correlated better with the capillary absorption than did the permeability results. This was not a surprise since the absorption test is a diffusion driven process, which is how the ions migrate through concrete to the steel, whereas the permeability test uses an applied voltage to drive the ions. Table 13 shows the permeability versus the corrosion ranking, and Table 14 shows the capillary absorption versus the corrosion ranking. Finally, the 80% PC + 20% FA mixture was not included since a less corrosion-resistant bar was used as reinforcement, which would naturally skew the results.

**Table 12. Estimated Area of Corrosion on Tombstone Ready-Mix Samples**

| Rank | Mixture | Steel Type | Area of Corrosion ($in^2$) | Image of Exposed Surface Shown in |
|---|---|---|---|---|
| 1 | 60% PC + 40% Slag | ASTM A1035 (ASTM, 2004) | 0 | Figure 6 |
| 2 | 72.5% PC + 25% Slag + 2.5% SF | ASTM A1035 | 4.531 | Figure 7 |
| 3 | 100% PC | ASTM A1035 | 10.47 | Figure 8 |
| 4 | 50% PC + 25% FA + 25% Slag | ASTM A1035 | 16.45 | Figure 9 |
| 5 | 82.5% PC + 15% FA + 2.5% SF | ASTM A1035 | 19.192 | Figure 10 |
| 6 | 93% PC + 7% SF | ASTM A1035 | 23.07 | Figure 11 |
| 7 | 80% PC + 20% FA | Carbon steel | 129.337 | Figure 12 |

PC = portland cement; SF = silica fume; FA = fly ash.

Figure 6. 60% PC + 40% Slag Ready-Mixed Batch

Figure 7. 72.5% PC + 25% Slag + 2.5% SF Ready-Mixed Batch

Figure 8. 100% PC Ready-Mixed Batch

Figure 9. 50% PC + 25% FA + 25% Slag Ready-Mixed Batch

**Figure 10. 82.5% PC + 15% FA + 2.5% SF Ready-Mixed Batch**

**Figure 11. 93% PC + 7% SF Ready-Mixed Batch**

Figure 12. 80% PC + 20% FA Ready-Mixed Batch

Table 13. Permeability Versus Corrosion Ranking

| Permeability Response (highest permeability to lowest) | Ranking Based on Corrosion Area (1 = smallest corroded area) |
|---|---|
| Straight cement | 3 |
| Ternary: 15% Fly Ash + 2.5% Silica Fume | 5 |
| 7% Silica Fume | 6 |
| 40% Slag | 1 |
| Ternary: 25% Fly Ash + 25% Slag | 4 |
| Ternary: 25% Slag + 2.5% Silica Fume | 2 |

Table 14. Capillary Absorption Versus Corrosion Ranking

| Capillary Absorption Response (highest absorption to lowest) | Ranking Based on Corrosion Area (1 =smallest corroded area) |
|---|---|
| Ternary: 15% Fly Ash + 2.5% Silica Fume | 5 |
| 7% Silica Fume | 6 |
| Straight cement | 3 |
| Ternary: 25% Fly Ash + 25% Slag | 4 |
| 40% Slag | 1 |
| Ternary: 25% Slag + 2.5% Silica Fume | 2 |

# VCTIR Concrete

## VCTIR Concrete Tests

As shown in Table 15, workable concretes with slump values ranging from 2.5 to 4.8 in and air contents from 4.0% to 8.0% were attained; all values met the VDOT specifications. These specimens were all prepared with uncoated carbon steel reinforcement.

The compressive strength results were satisfactory; at 28 days they were above 4,000 psi, and at 1 year they were above 6,000 psi (Figure 13). The long-term results indicated that concretes with SCMs had higher compressive strengths than the control mixture. It was also interesting to note the influence of time on these mixtures by comparing the 28-day and 1-year strengths. All of the samples increased in strength over time; however, they did not all increase by the same percentage. The modulus of elasticity values ranged from 2.9 x $10^6$ psi to 3.7 x $10^6$ psi at 28 days, and at 1 year the values were about 3.8 x $10^6$ psi and more (Figure 14). Trends similar to those for compressive strength were observed; the control concrete had the lowest modulus of elasticity.

**Table 15. Fresh Properties of VCTIR Concrete Batches**

| **Cast Date** | 4/21/09 | 4/23/09 | 4/28/09 | 4/30/09 | 5/5/09 | 5/7/09 | 5/12/09 |
|---|---|---|---|---|---|---|---|
| **Mixture** | 100% PC | 80% PC + 20% FA | 60% PC + 40% Slag | 93% PC + 7% SF | 50% PC + 25% FA + 25% Slag | 72.5% PC + 2.5% SF + 25% Slag | 82.5% PC + 2.5% SF + 15% FA |
| **Slump (in)** | 4.8 | 3.5 | 5.0 | 4.0 | 4.8 | 2.5 | 4.8 |
| **Air content (%)** | 8.0 | 5.6 | 7.9 | 4.0 | 4.8 | 5.9 | 6.8 |
| **Concrete temperature (°F)** | 80 | 78 | 79 | 79 | 78 | 78 | 76 |
| **Air temperature (°F)** | 75 | 75 | 75 | 75 | 75 | 76 | 75 |
| **Relative humidity (%)** | 46 | 34 | 53 | 43 | 49 | 51 | 48 |
| **Density (lb/ft$^3$)** | 140 | 143.2 | 145.6 | 141.6 | 138.8 | 143.2 | 141.2 |

PC = portland cement; FA = fly ash; SF = silica fume.

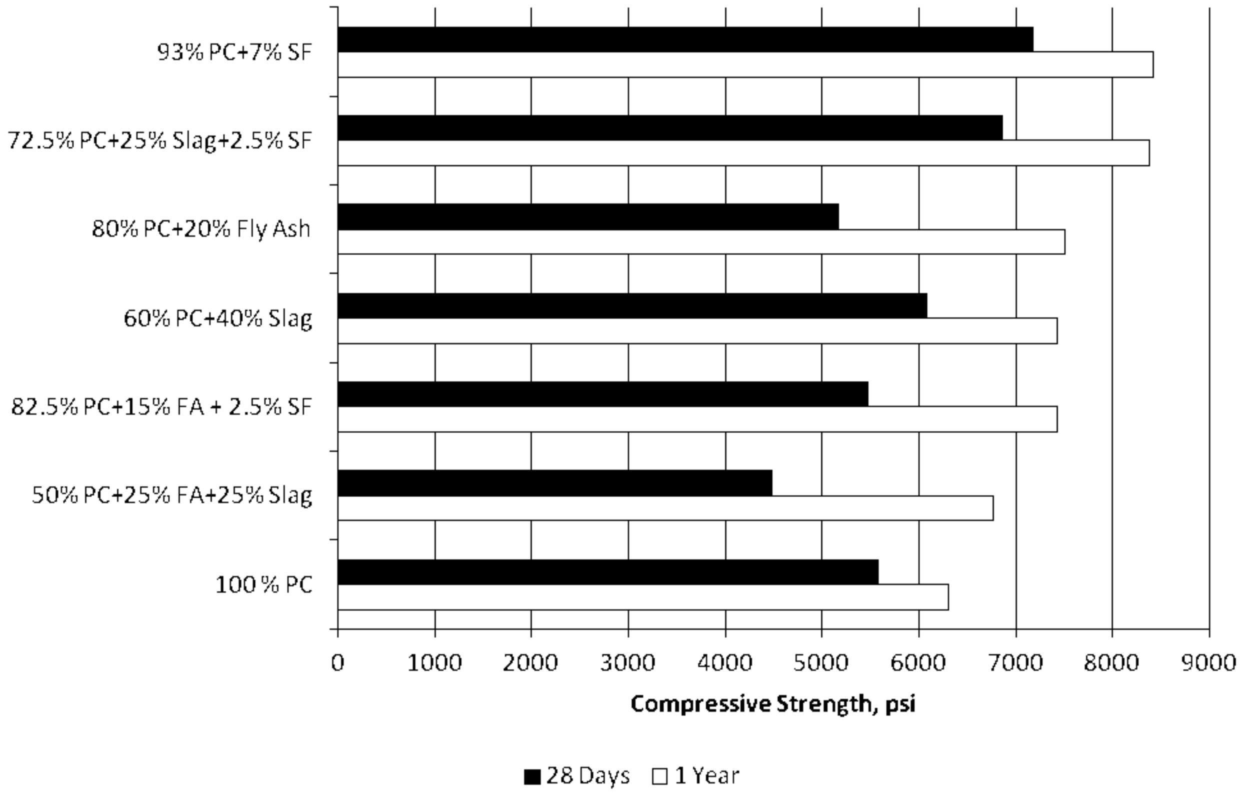

Figure 13. Compressive Strength Data for VCTIR Mixtures

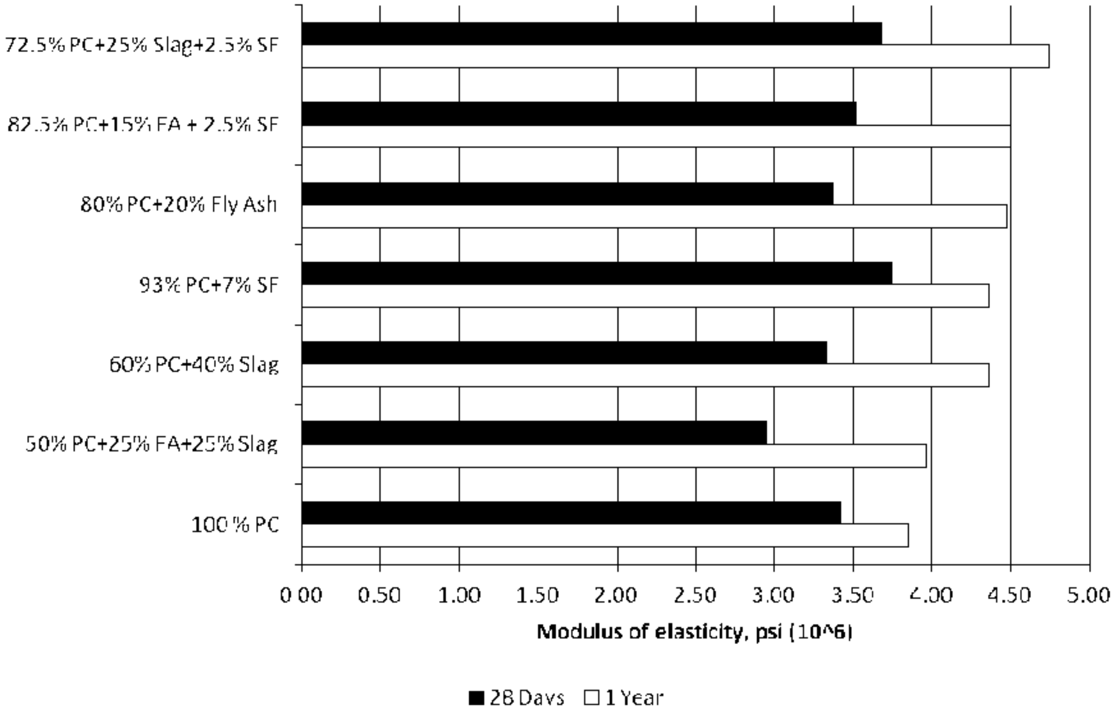

Figure 14. Modulus of Elasticity Data for VCTIR Mixtures

The permeability results for the VCTIR mixtures are provided in Figure 15. Similar to the permeability results for the ready-mix concrete, the addition of SCMs reduced the amount of charge passed after 28 days and reduced it even more after 1 year. Not only was there a reduction in permeability over time, but the 28-day permeability results also reproduced the relative ranking of the mixtures when compared with the 1-year result.

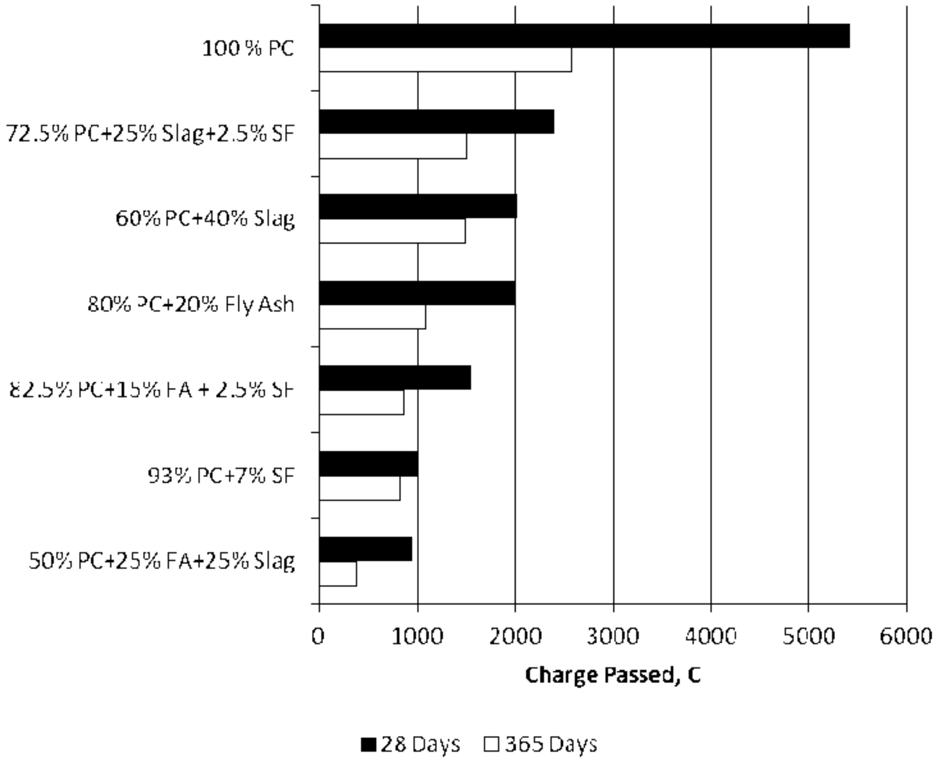

**Figure 15. Permeability Data for VCTIR Mixtures**

## Corrosion Testing of VCTIR Concrete

The response of the reinforcing steel as a result of the tombstone testing indicated that the different mix designs strongly influenced the amount of corrosion on the reinforcing steel. Although these seven different mixtures were cast over a period of 21 days, the blocks were allowed to cure for more than 11 weeks before being exposed to saltwater. The mixtures were prepared on different days, but all the specimens were exposed to saltwater on the same day. These specimens were exposed to the saltwater ponding cycle for a little over 46 months and then allowed to remain dry for another nearly 10 months before they were autopsied.

Upon autopsy of the specimens, corrosion was detected within each group of mixtures and the area was measured and recorded in Table 16. Figures 16 through 22 show photographs of each specimen. As indicated in Table 16, the 60% PC + 40% Slag showed the smallest area of corrosion, which can be seen in Figure 16, and revealed the value of slag in both the ready-mixed and VCTIR mixtures. Unlike with the earlier ready-mixed concretes, however, the 100% PC concrete had the worst result, which can be seen in Figure 22, which clearly demonstrated the benefit of including SCMs in concrete mixtures.

These results showed that SCMs can improve the concrete mixture by impeding the movement of chlorides through the concrete. Further, the pH, which is also influential in improving the corrosion resistance of the steel, is not always greatly decreased by the addition of SCMs.

**Table 16. Estimated Area of Corrosion on Tombstone Laboratory Mixture Samples**

| Rank | Mixture | Steel Type | Area of Corrosion ($in^2$) | Image of Exposed Surface Shown in |
|---|---|---|---|---|
| 1 | PC 60% + Slag 40% | Carbon steel | 4.128 | Figure 16 |
| 2 | PC 72.5% + Slag 25% + SF 2.5% | Carbon steel | 4.500 | Figure 17 |
| 3 | PC 93% + SF 7% | Carbon steel | 18.771 | Figure 18 |
| 4 | PC 80% + FA 20% | Carbon steel | 25.372 | Figure 19 |
| 5 | PC 82.5% + FA 15% + SF 2.5% | Carbon steel | 25.933 | Figure 20 |
| 6 | PC 50% + FA 25% + Slag 25% | Carbon steel | 34.354 | Figure 21 |
| 7 | PC 100% | Carbon steel | 101.548 | Figure 22 |

PC = portland cement; SF = silica fume; FA = fly ash.

Figure 16. VCTIR PC 60% + Slag 40% Mix Design

**Figure 17. VCTIR Slag 25% + SF 2.5% Mix Design**

Figure 18.  VCTIR SF 7% Mix Design

Figure 19. VCTIR FA 20% Mix Design

Figure 20. VCTIR FA 15% + SF 2.5% Mix Design

**Figure 21. VCTIR FA 25% + Slag 25% Mix Design**

**Figure 22. VCTIR PC 100%**

## CONCLUSIONS

- The capillary absorption test at 1 year showed a reasonable correlation with the corrosion ranking results.
- The 28-day accelerated permeability test was a good predictor of the relative ranking of the 1-year results.
- In both the ready-mixed and VCTIR mixtures, the 60% PC + 40% Slag mixture exhibited the least amount of corrosion of the reinforcing steel after prolonged exposure to saltwater.
- The use of an SCM in concrete can improve the service life of a reinforced concrete structure by reducing the corrosion damage on the embedded steel, which leads to cracking and spalling of the concrete.

- In the laboratory tests, the control concretes exhibited the greatest degree of corrosion. However, when the same type of reinforcement was considered, in the ready-mixed concrete tests, the worst results were obtained when silica fume was used. More care must be taken to ensure the quality of the concretes containing silica fume produced in the truck mixers. The two issues are the addition of extra water and adequate mixing when silica fume is used.

- Different SCM mixtures had varying responses to the intrusion of chloride ions and the initiation and propagation of corrosion on the embedded reinforcing steel. However, as demonstrated by the controlled laboratory mixtures, all SCM additions improved the quality and corrosion resistance of concretes.

## RECOMMENDATIONS

1. *VDOT's Materials Division and VDOT's Structure and Bridge Division should continue to use supplementary cementitious material such as slag cement, fly ash, and silica fume if proven effective.* This change will ensure more durable reinforced concrete structures and is expected to provide better corrosion protection of the embedded steel.

2. *VDOT's Materials Division and VCTIR should work together to evaluate the different levels of protection provided by different types of SCMs as well as SCMs from different sources.* This will eliminate SCMs with a low impact on corrosion resistance.

3. *VDOT's Materials Division and VDOT's Structure and Bridge Division should consider using the absorption test in ASTM C1585 (ASTM, 2013b) to predict the corrosion protection provided by the concrete.*

## BENEFITS AND IMPLEMENTATION PROSPECTS

This study benefited VDOT because corrosion is the most common deterioration mechanism in reinforced structures. Rehabilitation of corroded structures results in large costs to VDOT. Although the use of SCMs improves the corrosion resistance of reinforced concretes, this study showed that the level of protection varies. Further, it is known that cracks in reinforced concrete are common and can facilitate the movement of chlorides to the reinforcing steel, which can initiate corrosion. Therefore, VCTIR should continue to investigate concrete with and without cracks.

The next step is for VDOT/VCTIR to look more closely at the types of SCMs VDOT uses and evaluate the different sources. During this step, care should be taken to determine if there are certain applications where some types of SCMs would be more suitable than others. VDOT/VCTIR should also evaluate using the absorption test as a means of assessing the level of corrosion protection provided by different concrete mix designs.

Finally, VDOT/VCTIR should continue their use of CRR and SCMs. The test results in this study showed the benefits of ASTM A1035 steel, one type of CRR, compared to carbon steel reinforcement as well as the corrosion protection provided by SCMs.

## ACKNOWLEDGMENTS

The authors recognize the contributions made by Cesar Apusen, Michael Burton, Matthew Felts, Gail Moruza, Arthur Ordel, and Michael Sprinkel.

## REFERENCES

ASTM International. ASTM A1035: Standard Specification for Deformed and Plain, Low-Carbon, Chromium, Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards, Vol. 01.04.* West Conshohocken, PA, 2004.

ASTM International. ASTM C469: Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates.* West Conshohocken, PA, 2010.

ASTM International. ASTM C39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates.* West Conshohocken, PA, 2012a.

ASTM International. ASTM C143: Standard Test Method for Slump of Hydraulic-Cement Concrete. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates.* West Conshohocken, PA, 2012b.

ASTM International. ASTM C173: Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates.* West Conshohocken, PA, 2012c.

ASTM International. ASTM C1064: Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates.* West Conshohocken, PA, 2012d.

ASTM International. ASTM C1202: Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates.* West Conshohocken, PA, 2012e.

ASTM International. ASTM C138: Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates.* West Conshohocken, PA, 2013a.

ASTM International. ASTM C1585: Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates.* West Conshohocken, PA, 2013b.

Glass, G.K., and Buenfield, N.R. The Inhibitive Effects of Electrochemical Treatment Applied to Steel in Concrete. *Corrosion Science,* Vol. 42, 2000, pp. 923-927.

Hartt, W.H., Powers, R.G., Lysogorski, D.K., Liroux, V., and Virmani, Y.P. *Corrosion Resistant Alloys for Reinforced Concrete.* FHWA-HRT-07-039. Federal Highway Administration. McLean, VA, 2007.

Hausmann, D.A. Steel Corrosion in Concrete: How Does It Occur? *Materials Performance,* Vol. 6, No. 19, 1967, pp. 19-23.

Lane, D.S. *Effect of Wet Curing Duration on Durability Parameters of Hydraulic Cement Concretes.* VTRC 10-R11. Virginia Transportation Research Council, Charlottesville, 2010.

Presuel-Moreno, F., Scully, J.R., and Sharp, S.R. *Identification of Commercially Available Alloys for Corrosion-Resistant Metallic Reinforcement and Test Methods for Evaluating Corrosion-Resistant Reinforcement.* VTRC 08-R21. Virginia Transportation Research Council, Charlottesville, 2008.

Sharp, S.R., Lundy, L.J., Nair, H., Moen, C.D., Johnson, J. B., and Sarver, B.E. *Acceptance Procedures for New and Quality Control Procedures for Existing Types of Corrosion-Resistant Reinforcing Steel.* VCTIR 11-R21. Virginia Transportation Research Council, Charlottesville, 2011.

Virginia Department of Transportation. *Road and Bridge Specifications*. Richmond, 2007.

Virginia Department of Transportation. *Corrosion Resistant Reinforcing Steels (CRR).* Instructional and Informational Memoranda, IIM-S&B-81.5. August 22, 2012. http://www.extranet.vdot.state.va.us/locdes/electronic%20pubs/Bridge%20Manuals/IIM/SBIIM.pdf. Accessed May 27, 2014.