

Design of Artificially Cracked Concrete Specimens for Virginia Department of Transportation Material Evaluation

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FINAL REPORT

**DESIGN OF ARTIFICIALLY CRACKED CONCRETE SPECIMENS FOR VIRGINIA
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ABSTRACT

The penetration of chloride ions and moisture through cracks in reinforced concrete structures can accelerate the corrosion of steel reinforcement and shorten the service life of the structure. The purpose of this study was to develop a method for simulating cracks of varying widths in concrete as a means of assessing various methods that are used to reduce the detrimental effects of cracks in reinforced concrete bridge decks. Once a promising design using shims set in concrete to simulate cracking was achieved, the specimens with simulated cracks were used to evaluate two materials that are routinely used by the Virginia Department of Transportation (VDOT) to reduce damage in reinforced concrete with cracks. The two materials were crack sealant and corrosion-resistant reinforcement.

The study developed removable shim designs that provided for a more rapid acceptance and quality control corrosion test for crack sealant products. The designs also provided for an indication of the sealants' ability to restrict chloride intrusion into a crack and the subsequent initiation of corrosion. In addition, a permanent shim constructed using Type 5 filter paper attached to Permacel double-sided tape provided a controlled way of testing the corrosion resistance of different types of corrosion-resistant reinforcement. Finally, it was determined that water-soluble shims formed a semisolid mass while being dissolved with water that sealed the crack openings and did not provide the crack needed to evaluate the behavior of sealant materials.

The study also found that Type 25, Type 4095, and MX-45 sands were not optimal for comparing the relative penetration performance of the crack sealants but that the MX-45 sand specified by Virginia Test Method (VTM) 101 should continue to be used. Although all six sealants evaluated met the requirements of VTM 101, the most promising sealants based on greater crack penetration and retention of the coating on more area of the crack face were a high molecular weight methacrylate and two low viscosity epoxies. Using these sealants at room temperature, workers have at least 5 minutes but less than 15 minutes on average to work sealants into cracks for greater than 95% penetration. Finally, the 4-oz waxed paper cups specified in VTM 101 were not available.

The study recommends that VDOT revise VTM 101 to specify a 5-oz waxed paper cup that is readily available. Further, the Virginia Transportation Research Council and VDOT's Materials Division should continue to develop the filter paper shim design for a more rapid acceptance and quality control corrosion test for corrosion-resistant reinforcement and the removable shim design for a more rapid acceptance and quality control corrosion test for crack sealant products.

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INTRODUCTION

Cracks in reinforced concrete structures can allow for the penetration of chloride ions and moisture, which can accelerate the corrosion of steel reinforcement and shorten the service life of the structure. The formation of cracks in concrete can result from the applied load, the water-cement ratio, drying shrinkage, or the method of concrete placement. Though cracks, such as those shown in Figure 1, are inevitable in reinforced concrete bridges, their detrimental effects can be minimized if certain measures are taken. These measures can often be integrated into the construction or maintenance of the bridge.

During construction, common methods for minimizing the effects of cracks on the service life of a structure include using steel that is resistant to corrosion, using concrete admixtures that reduce cracking, using pozzolans, using lightweight aggregate, and ensuring the concrete is properly placed and cured. An example is the Virginia Department of Transportation's (VDOT) use of corrosion-resistant reinforcing bar (hereinafter "rebar"),² which is known to have a higher resistance to corrosion when subjected to chloride ions as a result of salt exposure and can reduce additional maintenance needs in decks with cracks.^{1,3}

During bridge maintenance operations, hydrophobic concrete sealers can reduce the permeability of water and the infiltration of corrosion reactants through concrete. For example, Sprinkel⁴ observed that sealants can be useful in reducing the permeability of chloride ions in the top 2 in of cracked and uncracked sections of a concrete. Water-repellant/hydrophobic sealers such as stearates, silicones, and silanes chemically change the surface of concrete to repel water, whereas water-blocking sealers such as oil, mineral gum, epoxies, and acrylics fill voids in concrete.⁵



(a)



(b)

Figure 1. Cracks Near the Abutment. Cracks are evident in (a) the top of a reinforced concrete deck, with some of those cracks being continuous from the top to (b) the bottom of the deck where moisture can be seen seeping from the cracks. Arrows indicate the locations of several cracks.

Current sealants for sealing cracks and blocking water in steel-reinforced concrete include low viscosity epoxy, methyl methacrylate, high molecular weight methacrylate (HMWM), and urethane. HMWM sealer and water-dispersed epoxy have relatively low permeability. HMWM, for example, filled cracks to a depth of 0.5 in depending on the crack width.⁵

Since cracks can influence the service life of a structure, VDOT needed to have the ability to test and determine in the laboratory if the materials it uses to mitigate the damaging effects of cracks in the field would continue to meet its needs. The purpose of this study was to develop a method for simulating cracks of varying widths in concrete samples. The concrete

samples with the simulated cracks were then used as a means for assessing various methods that are used to reduce the detrimental effects of cracks in reinforced concrete bridge decks. This was done by developing different methods for creating artificially cracked samples; testing the penetration of saltwater and crack sealants in these artificial cracks; and then evaluating the initiation of rebar corrosion in concrete samples with sealed and unsealed artificial cracks.

PURPOSE AND SCOPE

The purpose of this study was to create consistent artificial cracks in small, manageable concrete specimens. This was done so that materials VDOT frequently uses to improve the durability of reinforced concrete could be evaluated in a comparable, easy, and timely manner.

Once a design was achieved to make promising artificially cracked specimens, these specimens were then used to evaluate two materials that are routinely used by VDOT to reduce damage in reinforced concrete with cracks. This was done to help demonstrate the usefulness of the cracked specimens and to test the performance of the materials.

The first crack mitigation method evaluated using an artificially cracked concrete specimen was the use of a crack sealant. Crack sealants are used on existing structures to stop chlorides and moisture from penetrating into a crack, which can mitigate corrosion damage of the reinforcing steel. The second corrosion mitigation method evaluated to mitigate damage in an artificially cracked specimen was corrosion-resistant reinforcement (CRR). CRR is placed during construction to ensure that corrosion is mitigated because of the inherent ability of the reinforcing steel to resist corrosion.

METHODS

Specimen Preparation

Mold Design

Three types of plywood molds for specimens were constructed. The first type of mold was approximately 7 in x 3.5 in x 2 in. A 5/8-in hole was cut at the 3.5 in x 2 in side of the mold to allow for the steel rebar to extend out of the concrete. The types of rebar tested are listed in Table 1. Two 0.037-in-thick slits were then cut into the 7 in x 2 in side of the box so the shims could extend to the exterior sides of the molds. The second type of mold measured 7.5 in x 4.5 in x 4 in with a 5/8-in hole for the rebar and included two 0.037-in-thick slits cut into the sides of this mold type, again to enable placement of the shims. The third type of mold, 14 in x 6.5 in x 2.75 in, also had a 5/8-in hole on 6.5 in x 2.75 in sides for rebar but no slit cut for shims (Figures 2 through 4).

Table 1. Artificial Crack Test Materials for Crack Feasibility, Corrosion, and Sealant Study

Purpose	Material	Removable or Permanent	Single Layer Thickness or Diameter	Abbreviation
Artificial crack: material removed by dissolving in water (water-soluble)	Aquasol	Removable	0.0033 in	AQ
	Associated Bag	Removable	0.0015 in	AB
	Extra Packaging	Removable	0.0032 in	EP
	MonoSol	Removable	0.0010 in	MO
Artificial crack: shim material	Polyurethane	Removable	0.008 in	PU
	Overhead transparency	Removable	0.004 in	OT
Artificial crack: tape to bind shim materials together	Polytetrafluoroethylene	Removable		PTFE
	Polypropylene	Removable		PP
	Permacel double-sided tape	Permanent		PDT
Artificial crack: medium-fast solution penetration rate	Type 1 filter paper	Permanent	0.0075 in	Type 1
Artificial crack: slow solution penetration rate	Type 5 filter paper	Permanent	0.0075 in	Type 5
Crack sealant test materials	SikaPronto 19 TF			HMWM 1
	T-70 MX-30			HMWM 2
	T-78			HMWM 3
	E-Bond 523			Epoxy 1
	Sikadur 55 SLV			Epoxy 2
	E-Bond 550			Epoxy 3
Sands for crack sealant penetration test	No. 45 (Sterling Sand, LLC)			MX-45
	No. 25 (Sterling Sand, LLC)			Type 25
	Granusil filter sand, No. 4095			Type 4095
Reinforcing steel for corrosion-resistant reinforcement test	ASTM A1035 low-carbon, chromium steel	Permanent	5/8 in	A1035
	2205 duplex stainless steel	Permanent	5/8 in	2205 SS
	ASTM A615 carbon steel	Permanent	5/8 in	A615

Shim Design

Shims were made from one of the materials listed in Table 1. The materials used were either removable (the shim would be removed from the specimen after casting) and shown in Figures 2 and 3 or permanent (the shim would become part of the test specimen) and shown in Figure 4. Each shim was cut using a paper cutter or scissors and had the dimensions of roughly 2 in x 7.5 in. Table 1 also shows the six sealant materials that were evaluated and the three sands that were used to compare the penetration of the sealants.



Figure 2. Mold and 1-Ply Shim Construction

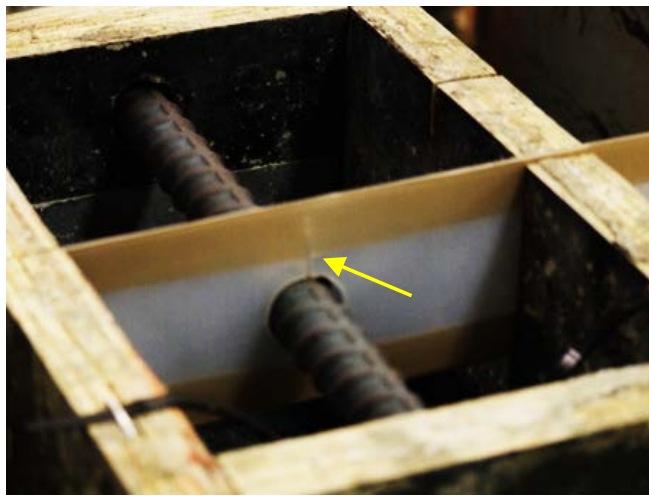


Figure 3. Perforated Multi-Ply Shim in Specimen Mold. Arrow is pointing to vertical cut in shim.

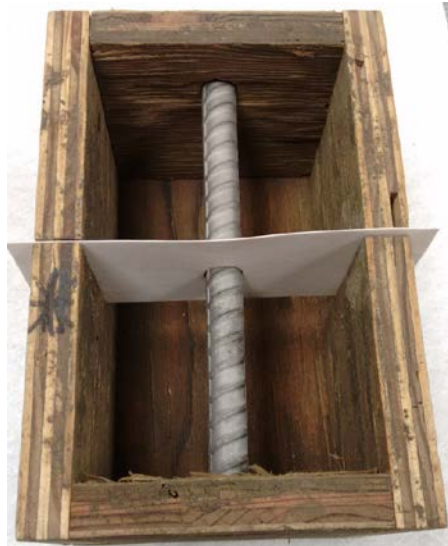


Figure 4. Permanent Shim Specimen Constructed Using Filter Paper on Permacel Double-Sided Tape

Mold Assembly

Completed shims were inserted into the slots of the assembled 7 in x 3.5 in x 2 in or 7.5 in x 4.5 in x 4 in molds and centered on the hole in the front of the mold. The shim was stapled to the outside of the mold. A No. 5 steel rebar was then inserted in the mold; care was taken to guide the rebar through the shim. A zip tie was then placed under the No. 5 steel rebar to support the rebar and eliminate pressure on the shim, as shown in Figure 2.

The polyurethane (PU) bag shim was then perforated vertically in a line along the middle of the shim through a punched hole, as shown in Figure 3. While this vertical cut was made, the shim was not completely severed, as a minimal amount of shim material was left intact so that the shim did not break during casting.

Concrete Mix Design and Specimen Casting

A VDOT A4 post and rail concrete mixture with a minimum 28-day compressive strength requirement of 4,000 psi was used for the composition of all specimens in this study. A typical batch mixture by weight for a quarter cubic foot volume is provided in Table 2.

Table 2. Typical Batch Mixture, Weight per Quarter Cubic Foot

Component	Amount, lb
Cement	5.9
Water	2.6
Coarse aggregate	13.5
Fine aggregate	15.9

Crack Evaluation

Removable Shim Specimens

Water-soluble Shims

The water-soluble shims, listed in Table 1, were tested for solubility in different temperatures of 50 ml of tap water. The three test temperatures were cold (32°F), warm (70°F), and hot (120°F). Three 1 in x 1 in strips of each soluble plastic were cut out and placed in 1 cup of water at one of the three temperatures. A timer was started when the soluble strips were placed in the beaker of water and stopped when there was no visual trace of solid soluble plastic left in the beaker. The water-soluble shim that dissolved completely without residue was selected for casting in concrete. If multiple water-soluble shims dissolved completely, the measured dissolution times would be used to select the shim that would be used in concrete. It was important that the shim material not dissolve while the concrete was being placed and that time was allowed for the concrete to set. The selected water-soluble shims were cast in the concrete and left to cure in the molds overnight.

After concrete specimens were cast, the concrete specimens with water-soluble shims were removed from the mold. Then, Plexiglas strips were affixed to the top face of the

specimens, creating a contained ponding region, and the diked specimens were ponded with 120 ml of deionized water. Once the water was placed into the dike containment, the timer began and stopped when the last drop of water penetrated. The opened top of the dike containment was completely covered and sealed with Parafilm to prevent any loss of water by evaporation.

Polyurethane and Overhead Transparency Shims

The PU and overhead transparency (OT) shims and associated sample fabrication materials are listed in Table 1. For the PU shims, the thickness of the crack was adjusted by stacking the individual plastic layers (e.g., 1-ply, 2-ply, 3-ply, etc.). These single layers were then taped together at the top and bottom to create a shim of a certain thickness using polytetrafluoroethylene (PTFE) tape for a set of shims and polypropylene (PP) tape for the other set. The shims, several PU sheets thick in most cases, had a hole in the middle that was made using a punch and die set. The shim could then be installed in the molds and a piece of rebar incorporated if desired. The ability to adjust the crack thickness with the removable shims would provide a means of determining whether a consistent crack thickness could be created. This could allow for more controlled testing of construction or maintenance repair materials for reinforced concrete. To create an even thinner crack than 1-PU (a shim constructed using an individual layer of polyurethane), an individual layer of OT shim was used. Following multi-ply specimen casting, the part of the tape sticking out from the shims was then cut with a knife so that the middle sheets could be removed.

Controlled Loading Specimens

The two previous approaches to creating a crack involved leaving the shim in the concrete sample until the concrete had hardened and then removing the shim. However, the 14 in x 6.5 in x 2.75 in specimens were different from the other two designs in that they were cast with a temporary shim that was removed immediately after concrete consolidation. The purpose of the shim was to minimize bridging of the aggregate where the crack would be formed during controlled loading.

After the casting of the concrete samples, removal of the shim after vibration, and curing for a sufficient time, the specimens were removed from the forms. The cracks on this set of specimens were then formed by applying controlled loading on opposing ends until they exhibited a visible transverse crack.

Permanent Shim Specimens

Using materials listed in Table 1 to form the permanent shims, an initial group of nine concrete specimens were cast. Three 6.5 in x 1.5 in strips were cut out of a single sheet of Type 1 filter paper (hereinafter “Type 1”), and three 6.5 in x 1.5 in strips were cut out of a single sheet of Type 5 filter paper (hereinafter “Type 5”). An additional six 6.5 in x 1.5 in strips of Type 5 were cut out to be applied on Permacel double-sided tape (PDT) to determine if this improved the durability of the permanent shim during casting. These six strips were cast as a double layer by applying two strips of Type 5 to each face of the PDT. All prepared shims were cast in concrete, were left in the concrete while it cured, and remained in the specimen during testing.

Chloride Analysis Using Energy Dispersive Spectroscopy (EDS)

To select between Type 1 and Type 5 shims for the permanent shim specimens, test blocks containing one of the two shim types were cast, cured, and ponded with saltwater. These test blocks were first ponded with 3.5% NaCl solution for 8 hours. Then, one of each test block type was opened, exposing the paper shim along the face of the shim plane. EDS was performed along the exposed face of the test block to measure the chloride penetration distance from the surface of the specimen to the interior. Then, the six remaining test blocks were ponded again with 3.5% NaCl solution for two more cycles of 8 hours. EDS was then performed on the six remaining test blocks. The results of the EDS chloride concentration measurements were then reviewed and used to select the permanent shim specimen design.

Crack Measurements on Specimens

After the specimens with manufactured cracks were removed from the molds, their crack widths were measured. The crack-measuring tool selected was a crack comparator card measuring in inches. Measurements were compiled into a single spreadsheet after all cracks had been measured. The test was blind with three technicians, each one performing measurements without seeing the results of the other two. Each technician was told to measure each crack (i.e., each side of every specimen) 5 times at equally spaced locations spanning the entire crack. The orientation of the specimens and cracks was kept consistent from technician to technician. An extra column of notes was added for the technicians to record any anomalies noted in the specimen. If the specimen had a full or partial failure (i.e., a whole or partial shim still stuck in one or both sides of the crack), it was left up to the technicians' discretion to decide whether width measurements were possible and, if so, which ones and how many could be made.

In addition to the crack comparator card, another method used for assessing the crack widths was water infiltration. The concrete specimens were diked and ponded with water to determine if the crack width influenced the rate of filtration. Deionized water (120 ml) was poured into the diked area of the specimen. The timer was started when the first drop of water passed through the opposing side of the crack and stopped when the final drop of water fell through. The time data were recorded for each crack width.

Crack Sealant Evaluation

To aid in the selection of a crack sealant for the corrosion portion of the study, various sealants were evaluated. The sealants were first evaluated with a penetration test using various types of sand. The sealants were then evaluated using artificially cracked specimens that were developed in accordance with the procedures previously described.

Sealant Penetration in Sand

Virginia Test Method (VTM) 101 was used to measure the sealant penetration in sand. This test required that twelve 4-oz waxed paper cups for each type of sealant be filled with 100 g of sand. The 12 cups were then grouped into three sets of 4 cups that contained filter sands MX-45, Type 25, and Type 4095. The weighed cups of sand were vibrated for 10 to 15 seconds, placed on the scale, and tared. Three epoxies and three HMWM sealants were selected from the VDOT approved list of crack sealants to have a variation of sealant properties. Once each sealant was mixed according to the manufacturer's specifications, the timer was started and 40 g of polymer was poured into 1 cup of each sand type. A sealant-dispensing cup made pouring sealant manageable while final gel time was measured. The added mass and temperature of polymer for each cup were recorded. After 5 minutes, another 40 g of polymer was poured into 1 cup of each sand type and the added mass and temperature of polymer for each cup were recorded again. This step was repeated once more at 15 and 30 minutes. If the polymer reached a gelatin consistency and did not move when the container was tipped to the side, the time was recorded as the gel time. The 12 polymers and sand matrices were allowed to cure overnight. After 24 hours, the wax cups were removed from the hardened polymer and sand matrix. Then, the hardened matrix was lightly brushed to remove loose filter sand sediments and the mass of each matrix was recorded. The recorded masses were used to calculate the percent polymer penetration with the following equation:

$$\text{Percent polymer penetration} = C/(A + B) \times 100$$

where

A = weight of 100 g of sand and paper cups

B = weight of 40 g of polymer

C = weight of hardened polymer sand matrix.

Sealant Penetration in Concrete

Before the application of sealant, the surfaces of 30 cracked concrete specimens were cleaned of foreign particles, oils, and surface moisture. The crack sealant was mixed to the manufacturer's standard. The sealant mixture was poured over the cracked surface and applied evenly with a roller or squeegee. The specimens were allowed to dry overnight. After 24 hours, the specimens were cut along the longest side of the specimen in order to have two equal halves of the crack. The crack width was measured again in accordance with the instructions outlined previously. The distance of the cured sealant from the top surface was recorded and compiled into a data table. Then, the cracked line perpendicular to the longitudinal cut was also opened. The two opened faces of the artificial crack were inspected to assess how well they were coated by the sealant.

This approach resulted in two additional methods being used to determine the effectiveness of the crack sealant: (1) an area measurement that is designated as the percent penetration, and (2) an area measurement that is specified as the percent coverage. The percent penetration was defined by the evidence of crack sealant from the top to the bottom of the

crack. The percent coverage was defined as the amount of area of the crack face that is covered with sealant.

CRR Evaluation

A total of 31 specimens were constructed with different shim and reinforcement materials for corrosion and sealing purposes. There were 15 reinforced concrete specimens with permanent shims: 5 A615, 5 A1035, and 5 2205 SS specimens. There were 10 A615 specimens with removable shims. Another 6 A615 specimens were cast without shims, but 5 of the 6 specimens would be cracked in flexure by loading using a uniaxial compression frame. The concrete specimens were placed in lime water for 7 days after casting. After 7 days, the specimens were left to dry overnight at room temperature. Then, they were scrubbed with a sponge and water and dried. Once dried, the surfaces of the crack specimens were cleaned of any foreign particles. One HMWM sealant was used to seal 5 A615 specimens with a crack formed using a PU shim and 3 A615 specimens with a crack that was formed by loading. The 8 sealed specimens were tested to determine the corrosion protection capabilities of sealed versus unsealed specimens. The sealed specimens were left to cure overnight. A containment dike assembled from thin Plexiglas was placed on the top face of each specimen with a caulk sealant, and the diked concrete was allowed to cure for another 24 hours. For 2 weeks, the area diked on the concrete specimens was ponded with deionized water for 3 days and dried for 4 days. The specimens were then ponded with 3.5% reagent grade NaCl solution in the same pattern of ponding and drying for 6 to 10 weeks. Corrosion potential readings were recorded twice a week when the specimens were wet and dry. These measurements were made in accordance with ASTM C876 using a saturated copper/copper sulfate electrode (CSE) as the reference electrode.

When the testing was concluded, the specimens were cut with a saw and broken to expose the rebar. The percent of corrosion on the surface area of the rebar was calculated by estimating the amount of corrosion products on the rebar section that was 2 in left of center and 2 in right of center. The 2-in regions were approximately five raised ribs right of the center of the rebar and five raised bars left of the center.

RESULTS AND DISCUSSION

Crack Evaluation

Removable Shims

Water-Soluble Shims

The water-soluble shims, AB, MonoSol (MO), and Extra Packaging (EP), are a polyvinyl alcohol material. Water-soluble Aquasol (AQ) is a mixture of methyl cellulose and wood pulp. The rankings from slow to fast for the water-soluble polymers in the three water temperatures with regard to solubility rates were EP, AQ, and MO. AB never completely dissolved in the cold (32 °F), warm (70 °F), and hot (120 °F) water; it became slimy and had a gel-like consistency.

EP dissolved completely in the hot (120 °F) water but became a semisolid mass, as shown in Figure 5, in cold (32 °F) and warm (70 °F) water. AQ dissolved but left wood pulp residue throughout the water. MO dissolved quickly and completely at all water temperatures within 3 minutes. EP and MO were therefore selected for casting because they completely dissolved without any residue.

After the concrete specimens were cast and ponded, the EP and MO water-soluble shims did not dissolve. The water-filled dike containment on the top of the concrete specimens did not infiltrate the specimens. Water-soluble shims did not create an open crack through the concrete; therefore, this mechanism was not a reliable technique for crack formation and it was determined that it should not be used for the subsequent sealant or corrosion testing.



Figure 5. Semisolid Extra Packaging (EP) Specimen (indicated with black arrow). The specimen is still undissolved in water after 24 hours.

PU and OT Shims

During fabrication of the 2 in x 7.5 in PU shims, the PU bags had a poor response to being cut by scissors; standard scissors creased them out of shape and did not cut them easily. The best solution was found to be the use of a paper cutter with an edge sharp enough to make a clean, straight cut. If properly cut, 18 in x 28 in PU bags could yield 58 single-sheet PU shims. To do this, 6 shims were initially made by making a parallel cut, 2 in wide, along the long edge of the bags (simultaneously cutting through two layers) and then sectioning this longer strip into 7.5-in-long shims. The remaining 16-in-wide PU sheet was then cut again in half, and the 8-in strips were placed on top of each other for ease of cutting with the paper cutter.

Three of the PU shims were folded on one side (using the natural fold of the PU bag they came from) to test whether this worked better than taping. The folds were placed facing upward as the concrete set. The remaining multi-ply shims did not have the natural fold, so they were taped. The PTFE tape and the PP tape were selected for several reasons. The PTFE tape was used because PTFE has the third-lowest coefficient of friction of any known solid material (0.05

to 0.10), theoretically preventing the tape from bonding to the concrete, so the shims could be pulled out easily. The PP tape was used as a more economical comparison. One-inch tape was used on both the top and bottom of each shim so that the amount of tape in contact with the concrete was minimized. The 1-ply PU shims and the vinyl shims (also 1-ply) did not need taping.

The OT shim material did not have some of the problems encountered with the PU shims. An OT shim with a thickness of 0.004 in was used because it was stronger and one-half the thickness of the PU shims. It also eliminated the need for PTFE or PP tape, which could introduce unknown variables. Both PU and OT shims were used in each specimen, producing two cracks; one crack was formed with a PU shim and the other with an OT shim. The supposition was that concrete specimens with those two shims would produce cracks widths of 0.008 in and 0.004 in, respectively

The final stage of specimen preparation was shim and mold removal from the concrete specimen. With PU multi-ply shims, the interior plastic layers were removed first to give the outside sheets more space in which to debond from the concrete, as shown in Figure 6. Then, the outside sheets were carefully pulled out from the specimen, initially by hand and then by the use of needle-nose pliers, neither of which applied even tension. To rectify this issue, the researchers manufactured a custom removal tool made out of a pipe with a slot cut in it for even pulling (Figure 7).



Figure 6. Removing Middle Layer of Multi-Ply Poly Shim First



Figure 7. Custom Shim Removal Tool

A vice grip was used on the end of the wrap tool to keep a constant force and increase leverage on the wrap tool while the shims were pulled out. Specimens were best placed on their side (shim facing up, i.e., on the top) to pull. This orientation made keeping torque on the wrap tool via the vice grips a more natural twisting motion.

If the shim started to tear, the best option was to try to affix the tearing portion back to the part still being pulled, either with tape or by pressure from fingers. However, even with careful pulling and the right tools, either some shims still got stuck inside the specimen or the end of the shims protruded out of the top of the concrete. With experience, the number of shim removal failures was minimized. Pressurized air from an air hose nozzle was blown between the shim and the concrete (on both sides) in an effort to loosen the bond between the shim and the specimen. Pressurized air was also used after the shims were pulled in order to blow out the dust and small pieces of dislodged concrete, if any, from inside the specimen.

For the unreinforced specimens, the removal of PU and OT shims to form cracks proved to be challenging initially. The first two trials of pulling out 1-ply PU and 1-ply OT shims had a success rate of 20% and 0%, respectively. It was found that unlubricated shims were difficult to remove. It was decided that since concrete cracks in the field might contain foreign contaminants such as dirt, oil, and grease that a minimal amount of lubricant could be applied to the shims. As a result, subsequent shims were coated with mineral oil in order to facilitate removal. Lubricating the shims improved the success rate for complete shim removal to 60%.

In addition to lubricating the shims in the unreinforced specimens, the investigators tested whether physically debonding the shims would reduce the failure rate during removal. To do this, the shims were pulled 1 in to the right and then 1 in to the left 3.5 hours after mixing. Then, the shims were removed from the specimen at 6 hours after the mixing, but the results were poor. The success rate remained between 20% and 60% for the four succeeding trials. One observation was that the concrete began to set quickly for some batches and not for others. As a consequence, the shims were pulled to 1 in to the right and left at 2 hours and then completely pulled out after 3 more hours. The success rate drastically improved from below 60% to 100% for the last five batches of concrete.

Table 3 lists the main challenges identified in removing the shims and corresponding solutions. Crack widths created using OT were more often closer to the thickness of the shim material compared to those of the PU-generated cracks, which can be seen in Figure 8. The most frequent measured thickness for the PU-generated crack was 0.007 in, however, which is only a 0.001-in difference compared to the thickness of the PU material. This might be attributed to the fact that the lubricated and unlubricated OT was easier to pull out without tearing or being caught in the concrete as the PU did because it was less elastic and sturdier.

It was also interesting that for both shims the graph of the data did not more closely resemble a normal distribution with the mean being close to the width of the shim used. Instead, the graphs appear to be closer to a multimodal distribution and most of the estimated crack widths were less than the thickness of the shim material. It is possible that this was due partly to the use of a crack comparator card to make measurements, as human error is possible with this method.

Table 3. Problems Encountered With Shim Removal and Corresponding Solutions

Problem	Solution
When pulling polyurethane bags from the concrete specimens, the polyurethane elongates and breaks.	Thoroughly oil shim slits in wooden molds.
Polyurethane bag binds to the concrete and cannot be removed.	Several hours after the concrete mixture is cast, pull shim 1 in to the right and 1 in to the left. Then, after several more hours of curing, pull out the shims with the custom shim removal tool.
Creased/bent areas on polyurethane bags lead to creased/bent shims.	Use the flattest polyurethane bags possible, or use shim material only from the flat part of the polyurethane bag.
Different sizes of single polyurethane sheets lead to warping when the sheets are taped together.	Take extra time marking out and cutting polyurethane bags with an appropriate tool (e.g., paper cutter). If shims are still not quite the same size, tape one long side, and then use a paper cutter to trim off the excess material. Exact crack widths are not as important as getting a flat, uniform shim.
Tape traps air bubbles, increasing the chance of catching and binding the shim to the concrete.	Fold tape uniformly from the middle to the outsides, and smooth it down slowly. Squeeze out any air bubbles to the closest side of the tape (top or bottom).
Creases or folds are formed in the tape itself while the shim is being taped together, increasing the chance of catching and binding the shim to the concrete.	Fold tape uniformly from the middle to the outsides, and smooth it down slowly. If necessary, use a sharp utility knife to cut the crease/fold, and flatten the tape by re-attaching it to itself.
Tape extends outside the shim area, binding to itself, and forms an area where the manufactured crack is not uniform (i.e., is much thinner).	Same as previous solution. Fold tape uniformly, and hold down the polyurethane sheets while taping.

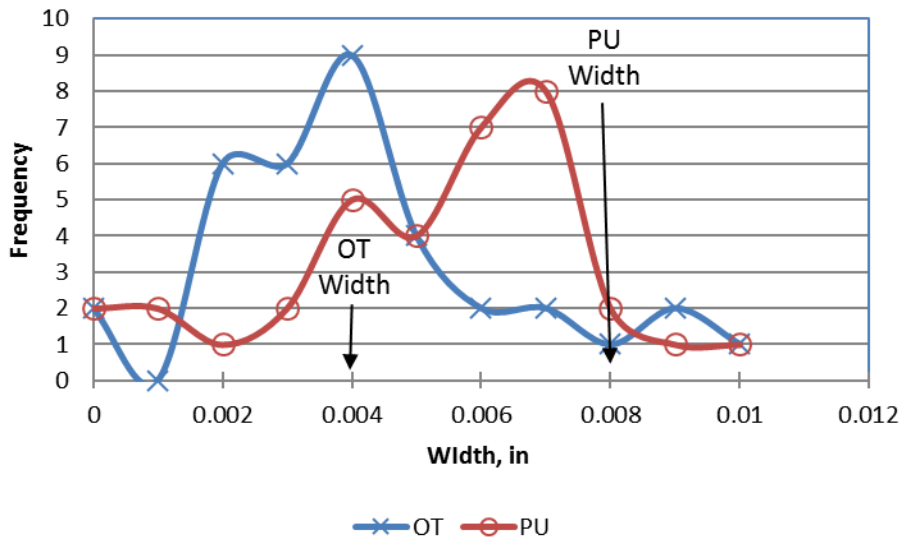


Figure 8. Distribution of Measured Crack Widths for OT- and PU-Formed Cracks. OT = overhead transparency; PU = polyurethane.

The final crack width measurements for a total of 70 cracks ranged from 0 to 0.01 in. The cracks created using OT had a higher frequency of cracks between 0.003 and 0.005 in (actual OT material width of 0.004 ± 0.001 in), with 54% of the OT samples having cracks falling within this range; the PU formed cracks between 0.007 and 0.009 in (actual PU material width of 0.008 ± 0.001 in), with only 32% of the PU samples falling within this range. For the PU-formed cracks to meet a criterion of more than 50% of the sample cast being considered acceptable, the range would need to be increased to ± 0.002 in, and then 55% of the samples would have been acceptable. Clearly, the OT material formed more consistent cracks when compared to the PU material.

Cracks formed using individual and multiple layers of PU do correlate with the thickness of the shims. From the exterior, the cracks formed using 1-ply PU shims were smaller in width than those formed using 2-ply PU shims, which were also smaller than those formed using 3-ply PU-layered shims. However, at the top exterior surface of the cracks in each specimen, there was some variation in width along the crack for specimens formed with the same number of PU shim plies. In addition, the average measurement of the 1-ply shims was probably skewed slightly because one of the individuals who performed the evaluation indicated that the crack was “closed” so a width of 0.0 in was assigned to the data being analyzed. The time it took for water to pass through cracks formed using 1-ply PU, 2-ply PU, and 3-ply PU shims was not linearly dependent on the exterior crack width, but there was a relationship between the number of shim plies and average time, as indicated in Table 4.

Table 4. Crack Width and Water Infiltration Times for Different PU Shim Plies

No. of PU Shim Plies	Crack Width, in		Time, sec	
	Average	Standard Deviation	Average	Standard Deviation
1	0.005	0.004	176	62
2	0.015	0.001	123	14
3	0.026	0.005	97	36

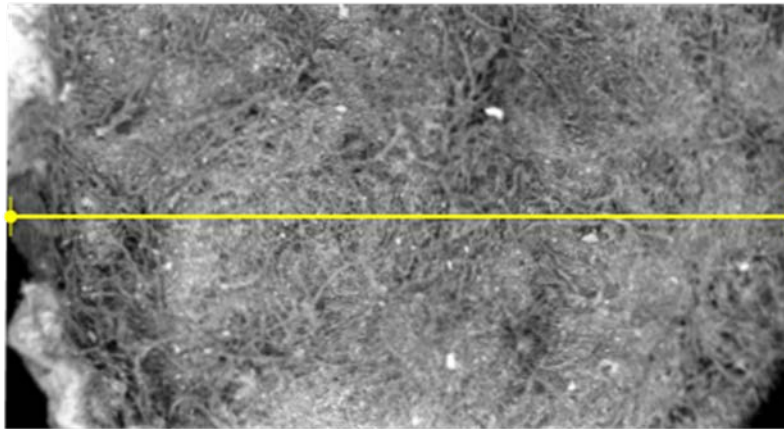
PU = polyurethane.

Permanent Shims

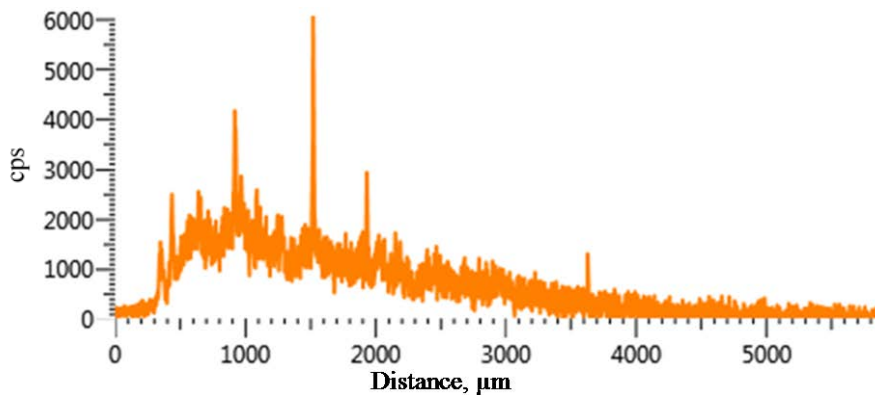
The last shim material considered for testing was a 0.0075-in-thick filter paper. Filter paper can be manufactured differently to have a slow, medium, or fast filtration rate. Of three types of shims constructed out of filter paper, the shim with Type 5 held by PDT had a higher penetration of NaCl solution according to the results of the EDS analysis, which are given in Table 5. EDS measurements, with a typical example shown in Figure 9, also indicated that the value for the penetration and concentration of the NaCl solution for the same shim after the three 8-hr cycles was much higher than the value for the single 8-hr cycle. The obvious explanation for the higher salt concentration through the PDT and two Type 5 layers is the additional thickness. Therefore, the Type 5 and PDT shim was used in the reinforced concrete mold. The double-sided tape also created a tougher shim that was more resistant to tearing when secured to the sides of molds.

Table 5. Penetration of NaCl Into Concrete

Shim Material	One 8-hr Cycle		Three 8-hr cycles	
	Penetration (mm)	% Cl penetration	Penetration (mm)	% Cl penetration
Type 1 filter paper	2.6	5.1	5.2	10.2
Type 5 filter paper	3.5	6.9	6.6	13.1
Type 5 filter paper with Permacel double-sided tape	5.9	11.7	9.7	19.1



(a)



(b)

Figure 9. Typical EDS Linescan. The linescan shows (a) the location of the linescan on the SEM image of the specimen, and (b) the results for chloride penetration on the permanent Type 5 filter specimen. SEM = scanning electron microscope; cps = counts per second.

Crack Sealant Evaluation

Sand Penetration

The degree of penetration of a crack sealant into sand provides an indication of the degree to which the sealant can penetrate a crack. Although actual cracks in the field are not standard sizes, a specified sand gradation can be selected as a control situation, allowing the comparison of the penetration of various crack sealants. Since 1995, VDOT has specified a sand

gradation for the testing of crack sealants as an indicator of relative performance. Sand products from manufacturers can change over time. The company that provided the sand, MX-45, in 1995 changed ownership, and there was some question as to whether the sand grade could be obtained. Thus, MX-45 sand obtained from Sterling Sand, LLC, and two additional sand products were selected for the comparison of crack sealants; the sieve analyses are reported in Table 6. It was not possible to make comparisons between the MX-45 sand grade provided in 1995 and that provided in 2017 because of the unavailability of MX-45 sand from the former year. Although different sieve sizes were used in 1995 than in 2017, the data in Table 6 suggest that the MX-45 sand used in the current study (in 2017) is similar to the MX-45 used in 1995 (MX-45a).

Table 7 presents the properties of the crack sealants and the results of sand penetration tests. The penetrations were determined immediately after mixing (0 time) and 5, 15, and 30 minutes after mixing to provide an indication of the effectiveness of the sealant over time after mixing. The data for the percent penetration with time interval, gel time, and temperature were indicative of the importance of applying the sealant promptly. The actual working time observed during this study was up to 5 minutes less than the reported working time from the manufacturers' specifications. Overall, field workers have at least 5 minutes but less than 15 minutes on average to work sealants into cracks for greater than 95% penetration. After 15 minutes, the decrease in percent penetration was approximately as follows: 100% for HMWM 3; 40% for Epoxy 2; 30% for Epoxy 3; 20% for Epoxy 1; 5% for HMWM 2; and 0% for HMWM 1.

The sand penetration test with all three sands provided an indication of the relative change in the penetration of the sealants over time after mixing. Although in 1995 MX-45 sand performed better than other sand gradations in showing a difference between sealants, in this study all three sands showed similar performance for all sealants at 0 time after mixing. Figure 10 shows similar penetration for all five sealants with all three sands (Type 25, Type 4095, and MX-45) after the initial mix time ($t = 0$ min). Either today's sealants penetrate similarly after mixing or a different sand gradation is needed to show differences.

Table 6. Sand Grades Used in Penetration Tests

Sand Product	% Passing Sieve Sizes							
	No. 8	No. 16	No. 20	No. 30	No. 40	No. 50	No. 100	No. 140
MX-45 ^a				94.9			3.5	1.0
MX-45 rev	100.0	99.8	99.0	99.3	46.1	18.5	6.0	
MX-45	100.0	99.9	98.9		46.1			
Type 25	100.0	97.1	77.9		21.5			
Type 4095	100.0	100.0	97.4		2.4			

^aData are from an analysis done in 1995.

Table 7. Sealant Properties and Performance

Product	Viscosity (cps)	Pot Life (min)	Time Interval (min)	Sand Product						Gel Time (min)
				Type 25		Type 4095		MX-45		
				% Penetration	°F	% Penetration	°F	% Penetration	°F	
Epoxy 1	<100	20-30	0	97.7	85	99.5	88	99.7	88	25
			5	99.7	94	99.9	96	100.0	95	
			15	85.1	145	84.6	146	61.6	145	
			30	0.0		0.0		0.0		
Epoxy 2	105	20	0	94.9	84	99.1	97	99.4	85	21
			5	99.3	99	98.6	100	99.3	99	
			15	61.6	180	62.8	183	52.6	181	
			30	0.0		0.0		0.0		
Epoxy 3	300-500	25-30	0	100.3	85	100.2	88	91.3	86	26
			5	100.2	92	100.1	95	73.1	93	
			15	74.5	124	76.2	127	64.0	125	
			30	0.0		0.0		0.0		
HMWM 1	25	10-15	0	98.3	83	97.7	89	98.1	86	28
			5	98.5	103	99.1	101	98.3	102	
			15	99.7	91	99.8	92	99.6	92	
			30	57.9	127	52.7	131	48.1	131	
HMWM 2	10-25	50-60	0	93.4	89	97.0	93	93.4	94	30
			5	94.0	98	97.5	96	93.7	98	
			15	96.8	93	99.1	89	97.6	92	
			30	93.9	108	62.9	102	71.4	104	
HMWM 3	<5-10	15-20	0	95.3	82	95.9	89	96.2	85	11
			5	97.4	106	97.4	115	97.7	113	
			15	0		0		0	130	
			30	0		0		0		

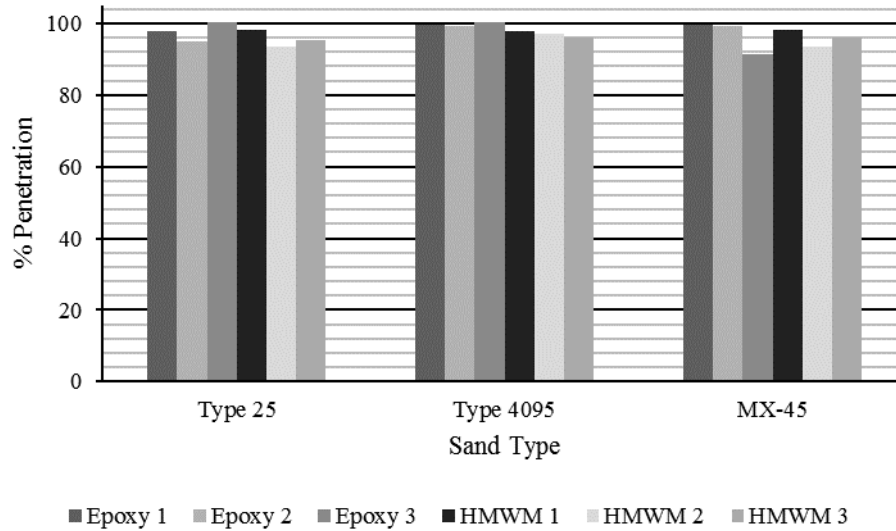


Figure 10. Sealant Penetration at 0 Time for the Different Sand Types Tested

VTM 101 specifies the use of 4-oz waxed paper cups, which were used in 1995 when the test was developed, but these cups could not be procured in 2017. The 4-oz paper cups without wax were used, but it was difficult to remove them completely from the hardened sand and sealant matrix. The paper cups were not suitable for use in testing since some permeable crack sealant leaked from the bottom and sides of the cup, as seen in Figure 11. In these cases, the paper cups that were permeable to the sealants would yield a lower percent penetration value because some of the sealant that penetrated leaked out. A waxed cup is less permeable. Therefore, it is important to use waxed paper cups in a size that is readily available. A Google search revealed that a 5-oz waxed paper cup is available, and it should be suitable for use with VTM 101. A revised version of VTM 101 that specifies 5-oz waxed paper cups is provided in the Appendix.



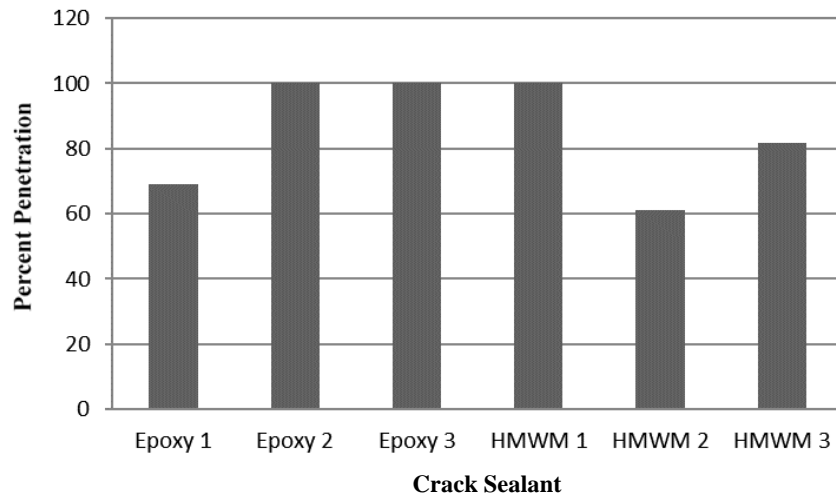
Figure 11. Epoxy Leaking Out of Paper Cups

Concrete Crack Penetration

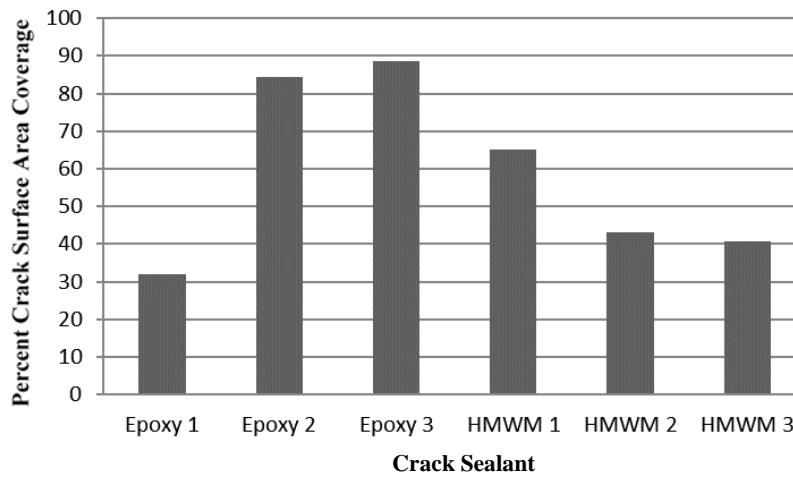
The percent penetration measurements indicated that Epoxy 2, Epoxy 3, and HMWM 1 exhibited 100% penetration for all crack widths, which can be seen in Figure 12a. The percent

penetration, however, varied sizably when HMWM 2, HMWM 3, and Epoxy 1 were evaluated. Using the percent crack surface area method of analysis to compare the six polymers, HMWM 1, Epoxy 2, and Epoxy 3 again consistently had the greatest sealant coating on the crack face, as shown in Figure 12b.

Although the sealant application time varied by several seconds between each specimen, the variation was not significant enough to determine if there was a dependency with time. The variation of crack widths with sealant suggested that the crack sealing properties of the sealants used were not exclusive to a specific crack. The order of increasing sealant percent penetration was as follows: HMWM 2 < Epoxy 1 < HMWM 3 < (HMWM 1 \approx Epoxy 2 \approx Epoxy 3). The order of increasing area of covered cracked face was as follows: Epoxy 1 < HMWM 3 < HMWM 2 < HMWM 1 < Epoxy 2 < Epoxy 3. Thus, the most promising sealants that demonstrated greater crack penetration and coated a larger area of the crack face were HMWM 1, Epoxy 2, and Epoxy 3.



(a)



(b)

Figure 12. Crack Concrete Penetration. (a) Average Percent of Sealant Penetration; (b) Average Percent of Crack Surface Area Covered With Crack Sealant.

Evaluation of CCR

During up to 7 weeks of exposure to 3.5% NaCl solution, corrosion potential readings were used to indicate corrosion of the rebar. The corrosion test was terminated for each type of steel after the reading for the steel had a value of -350 mV vs. CSE for more than two measurements. The potential reading of the A615 steel was the first to reach the level of a high likelihood of having corrosion (<-350 mV), followed by that of A1035 steel, according to Figure 13. That of the 2205 SS rebar specimens remained in the potential range that indicated the least likelihood of having corrosion. Upon breaking of all the specimens, it was confirmed that the specimens with 2205 SS rebar had no signs of corrosion product on the outer surface area of the rebar. The A615 steel rebar had the most corrosion product. The corrosion product on the rebar surface area of the specimens with A1035 steel ranged between that of the 2205 SS and that of the A615 steel rebar. On average, only 8% of the rebar surface area was corroded on the A1035 steel and 16% of the rebar surface was corroded on the A615 steel rebar. The time to corrosion was more than twice as long for the A1035 compared to the A615 steel rebar.

In addition to the study of the 15 specimens, there was an investigation of the ability of crack sealant to minimize corrosion in 10 cracked specimens, with all these specimens reinforced with A615 steel rebar. HMWM 1 was selected to be applied on the cracked concrete for corrosion testing because there was a sufficient quantity for testing and it was the second best sealant in the concrete crack penetration test. HMWM 1 was applied on a small section near and over the cracked face of 5 of the 10 concrete specimens with removable shims. The other 5 specimens with removable shims were not sealed.

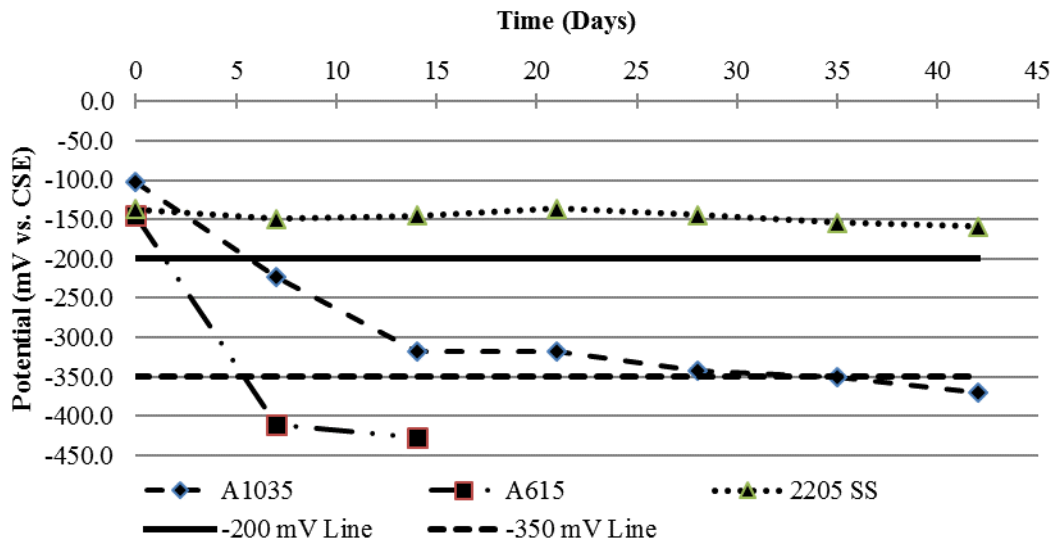


Figure 13. Average Corrosion Potential for Specimens With Filter. Note that according to ASTM C876, the -200 mV line indicates that values more positive are associated with a low probability of corrosion and values more negative are associated with an uncertain probability. The -350 mV line indicates that values more positive are associated with an uncertain probability of corrosion and values more negative are associated with a high probability of corrosion.

When all the specimens were ponded with 3.5% NaCl solution over 7 weeks, the sealed specimens remained more positive than -0.2 mV vs. CSE in comparison to their unsealed counterparts, which became more negative than -0.35 mV vs. CSE after the first 3 weeks, as seen in Figure 14. There was an average of less than 1% corroded surface area on the rebar in the 5 sealed specimens. Four of the sealed specimens had fairly similar amounts of corrosion products on the rebar surface area. The sealant layer on the fifth specimen cracked and likely allowed for the infiltration of chloride solution because 4% of the rebar surface coverage had corrosion. This indicates that this test could be a way of evaluating sealants, but additional replicate testing is required to determine statistical variability.

On the other hand, for the 4 unsealed specimens, about 5% of the rebar surface area was covered with corrosion, which was expected to be higher than for the sealed crack specimens since the chloride solution was probably able to reach the bar quickly. The fifth unsealed specimen had no evidence of corrosion product. Upon autopsy of the specimens, this was found to be due to the infiltration of the crack by the epoxy used to seal the sides of the specimens restricting the opening to the rebar, as shown in Figure 15. This would indicate that greater care should be taken while sealing the sides of the specimens. Possibly a layer of foam or adhesive tape could be used to restrict the flow of the epoxy into the side of the sample. These results confirm that this approach for testing cracked concrete is promising for assessing the corrosion susceptibility of rebar after sealant is applied to a crack, which could be done by systematically comparing sealed and unsealed reinforced concrete specimens and then ranking them based on half-cell potential measurements and visual assessment of the bars and cracks after corrosion has initiated.

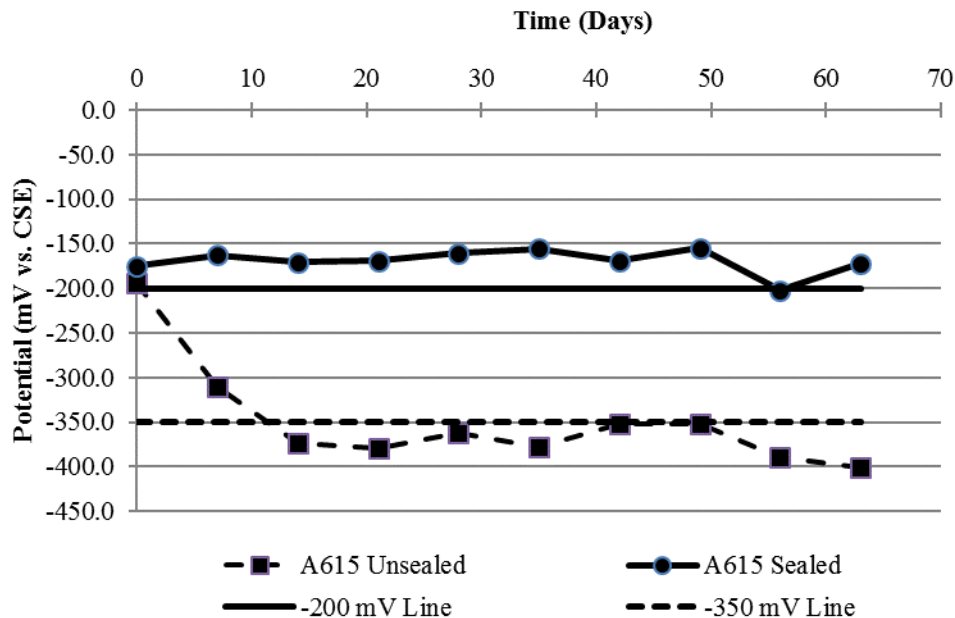


Figure 14. Average Corrosion Potential for Cracked Specimens. Note that according to ASTM C876, the -200 mV line indicates that values more positive are associated with a low probability of corrosion and values more negative are associated with an uncertain probability of corrosion. The -350 mV line indicates that values more positive are associated with an uncertain probability of corrosion and values more negative are associated with a high probability of corrosion.



Figure 15. Epoxy Restricting the Opening to the Rebar in an Unsealed Specimen

The last set of tests was performed on a collection of six specimens. With these specimens, one specimen was not cracked, to provide a baseline, and the other five specimens were cracked by loading using a uniaxial compression frame. Of the five cracked specimens, three were sealed and two were unsealed. The resulting crack widths in these specimens prior to sealing were 0.001 in or less. In this specimen group, half-cell measurements made during the 3.5% NaCl ponding cycle ultimately revealed that there was a high likelihood of corrosion with regard to the unsealed specimens, as shown in Figure 16. After the unsealed specimens were broken, there was light corrosion, 0.13%, on the uncracked specimen; the cracked specimens showed the greatest amount of corrosion, with 3.30% and 6.75% of the rebar surface covered with corrosion. Of the three specimens that were sealed, all three exhibited amounts of corrosion product that were between those of the uncracked and the cracked but unsealed specimens.

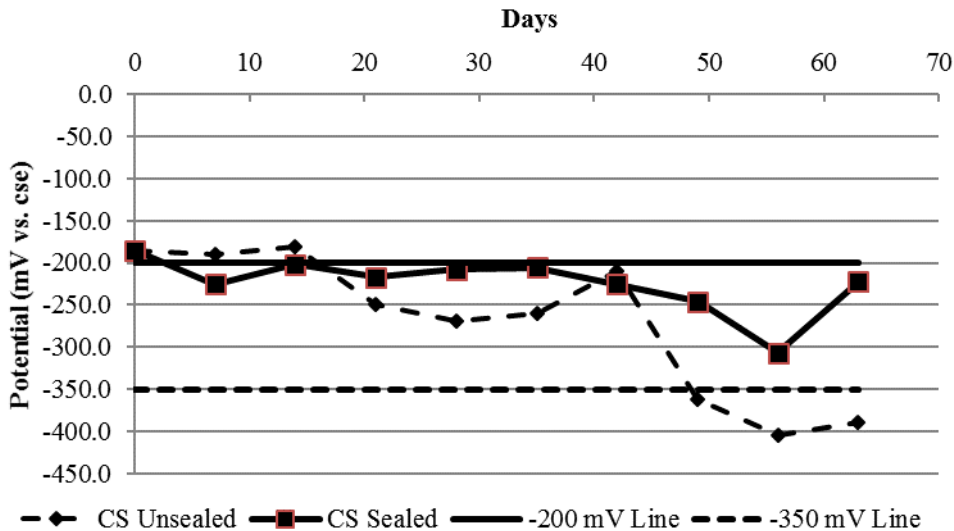


Figure 16. Average Corrosion Potential for Cracked Specimens by Loading. Note that according to ASTM C876, the -200 mV line indicates that values more positive are associated with a low probability of corrosion and values more negative are associated with an uncertain probability. The -350 mV line indicates that values more positive are associated with an uncertain probability of corrosion and values more negative are associated with a high probability of corrosion.

The cracked and sealed specimens exhibited a minor amount of corrosion with 0.25%, 0.27%, and 0.59% of the rebar surface covered with corrosion. It was interesting to note that the difference in the corrosion percentage between sealed and unsealed cracks was about 1 order of magnitude. The response of these test samples clearly indicates that sealing cracks can help mitigate corrosion and that this approach could be a useful way of evaluating a sealant's ability to alleviate corrosion in the field. By systematically comparing cracked and uncracked specimens with some sealed and others unsealed, it is possible that different sealants could be ranked based on the time it takes to initiate corrosion.

The test results revealed differences in corrosion potential between each rebar type. This is consistent with what was expected based on earlier studies. This was also validated by autopsying the samples and measuring the corrosion on the bars. It is also important, however, to understand the response of other corrosion-resistant steels using the methods developed in this study. Future research should include rebars with a high corrosion resistance such as austenitic and duplex stainless steel bars.

In this study, the researchers were able to develop a set of laboratory specimens of varying widths that could be used to evaluate materials VDOT uses to mitigate the damaging effects of cracks in the field. This method was then used successfully to create artificially cracked specimens for the testing of saltwater and crack sealant penetration, which was then followed by the initiation of rebar corrosion in concrete samples with sealed and unsealed artificial cracks.

CONCLUSIONS

- *Removable shim designs for a more rapid acceptance and quality control corrosion test for crack sealant products were developed. The use of these designs allowed an indication of the sealants' ability to restrict chloride intrusion into a crack and the subsequent initiation of corrosion.*
- *The permanent shims constructed using Type 5 filter paper attached to PDT provided a controlled way of testing the corrosion resistance of different types of CRR.*
- *Water-soluble shims formed a semisolid mass in the process of dissolving and sealed the crack openings.*
- *Paper cups that are not waxed are not suitable for use with VTM 101.*
- *The most promising sealants that demonstrate greater crack penetration and coat more area of the crack face are HMWM 1, Epoxy 2, and Epoxy 3.*
- *Using these sealants at room temperature, workers have at least 5 minutes but less than 15 minutes on average to work sealants into cracks for greater than 95% penetration.*

RECOMMENDATIONS

1. *VDOT's Materials Division should use the revised VTM 101 provided in the Appendix.*
2. *The Virginia Transportation Research Council (VTRC) should work with VDOT's Materials Division to continue the development of the filter paper shim design for a more rapid acceptance and quality control corrosion test for CRR.*
3. *VTRC should work with VDOT's Materials Division to continue the development of the removable shim design for a more rapid acceptance and quality control corrosion test for crack sealant products.*

BENEFITS AND IMPLEMENTATION

Benefits

- The benefits of implementing Recommendation 1 are improved accuracy and ease of procuring test materials when VTM 101 is performed.
- The benefit of implementing Recommendation 2 is the development of an acceptance test for CRR that is faster while still providing accurate results when compared to the standard AASHTO method.
- The benefit of implementing Recommendation 3 is the development of an acceptance test for crack sealant products that allows for variable crack widths and provides accurate results for acceptance and quality control corrosion testing.

Implementation

- Recommendation 1 will be implemented by VDOT's Materials Division by incorporating the changes shown in the revised version of VTM 101 provided in the Appendix. This will be completed within 1 year from the publication date of this report.
- Recommendation 2 will be implemented after VDOT's Materials Division and VTRC develop a draft VTM for CRR based on the results of this study. The draft VTM will then be tested independently at VDOT's Materials Division and VTRC to estimate variability with the test when performed at two different facilities. The draft VTM will be revised based on these findings, and the VTM will be finalized and ready for use as an acceptance test for CRR. This will be completed within 3 years from the publication date of this report.
- Recommendation 3 will be implemented after VDOT's Materials Division and VTRC develop a draft VTM for crack sealant products based on the results of this study. The draft VTM will then be tested independently at VDOT's Materials Division and VTRC to estimate

variability with the test when performed at two different facilities. The draft VTM will be revised based on these findings, and the VTM will be finalized and ready for use as an acceptance test for crack sealant products. Upon completion, this VTM will provide accurate results for acceptance and quality control testing when sealants are subjected to a corrosive environment. The final VTM will be completed within 3 years from the publication date of this report.

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REFERENCES

1. Sharp, S.R., and Moruza, A.K. *Field Comparison of the Installation and Cost of Placement of Epoxy-Coated and MMFX 2 Steel Deck Reinforcement: Establishing a Baseline for Future Deck Monitoring*. VTRC 09-R9. Virginia Transportation Research Council, Charlottesville, 2009.
2. Walus, K. *Corrosion Resistant Reinforcing Steels (CRR): Plan Modifications for Projects with CRR*. IIM-S&B-81.7. Virginia Department of Transportation, Structure and Bridge Division, December 13, 2016.
<http://www.viriniadot.org/business/resources/bridge/Manuals/IIM/SBIIM81.7.pdf>. Accessed August 29, 2017.
3. Scully, J.R., and Hurley, M.F. *Investigation of the Corrosion Propagation Characteristics of New Metallic Reinforcing Bars*. VTRC 07-CR9. Virginia Transportation Research Council, Charlottesville, 2007.
4. Sprinkel, M. *Evaluation of the Use of High Molecular Weight Methacrylate Monomers to Seal Cracks in Decks on I-81 Over the New River*. VTRC 91-R19. Virginia Transportation Research Council, Charlottesville, 1991.
5. Sprinkel, M. *Comparative Evaluation of Concrete Sealers and Multiple Layer Polymer Concrete Overlays*. VTRC 88-R2. Virginia Transportation Research Council, Charlottesville, 1987.

6. Gao, Z., Liang, R.Y., and Patbaik, A.K. Effects of Sustained Loading and Pre-Existing Cracks on Corrosion Behavior of Reinforced Concrete Slabs. *Construction and Building Materials*, Vol. 124, October 2016, pp. 776-785.
7. Sprinkel, M.M., and DeMars, M. Gravity-fill Polymer Crack Sealers. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1490, 1995, pp. 43-53.

APPENDIX

VIRGINIA TEST METHOD 101: DETERMINATION OF PENETRATION OF GRAVITY FILLED POLYMER CRACK SEALERS – (PHYSICAL LAB)

November 1, 2000, Revised September 2017

1. Scope

This method covers the procedure for determining penetration of polymers into a fine sand to access the polymers ability to penetrate fine cracks in Hydraulic Cement Concrete.

2. Apparatus

- a. 5 oz. (148 ml) wax paper cups, maximum dimensions of cup top-inside diameter, 2.5" (63.5-mm); bottom-inside diameter 1.75" (44.5-mm); height 2.75" (69.9-mm)
- b. MX-45 filter sand available from: Sterling Sand, LLC, 249 Laurel Road, Lexington, SC 29073, Phone: (866) 515-0965, www.sterlingsand.com.
- c. Quart can with inside rim removed
- d. 8 oz. (240 ml) plastic specimen cups
- e. Wood stirring stick or metal spatula
- f. Tared balance 2000 grams capacity
- g. Disposable gloves
- h. Polymer (epoxy, urethane, methacrylate)
- i. Stopwatch
- j. External Table Top-Vibrator
- k. Thermometer

3. Procedure

This test should be conducted at $25 \pm 2^\circ \text{C}$.

- a. Weigh 100 g of MX-45 filter sand into a 148 ml wax paper cup.
- b. Vibrate paper cups containing filter sand on vibrator for 10-15 seconds.
- c. Measure polymer components into 240 ml plastic specimen cups.
- d. Mix polymer components according to manufacturer's recommendation in a quart (liter) can using a metal spatula or wood stirring stick.
- e. Pour 40 grams of polymer on top the 100 g of filter sand in the 148 ml wax paper cup. Record weight of polymer (B).
- f. Allow the polymer and sand in the paper cup to set 24 hours.
- g. Remove as much of the paper cup from around the hardened polymer and sand matrix as possible and lightly brush any loose sand from matrix. Weigh the hardened polymer sand matrix (C).
- h. Calculate percent polymer penetration as

$$C \times 100 = \% \text{ penetration}$$

$$A+B$$

A = Weight of 100 grams Sand and paper cup

B = Weight of 40 grams Polymer

C = Weight of Hardened Polymer Sand Matrix

i. Report the percent penetration as average of three separate determinations.

5 oz. (147.8 ml) Wax Cup Dimensions

