

Durability of Post-Tensioning Grout Systems with Mixed-In Chlorides

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Benjamin L. Thiesse

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Eric Musselman

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Dedication

I would like to dedicate this to my family for all of their support.

Abstract

One of the most important properties of concrete and grout is its ability to protect the structural steel that is essential to post-tensioned concrete. The purpose of this report is to determine the effect of various concentrations of chloride ions on the long term durability of prestressing strands embedded in grout. To achieve this objective, samples were created to mimic portions of a post-tensioned duct. Each duct was given a unique combination of chloride and water that would create an ideal environment for corrosion to take place. With the results of testing to date, it is clear that the amount of chloride is the only variable that was tested that had a significant effect on the rate of corrosion. The amount of water and characteristics of the specimen had a few trends but nothing that would lead to the conclusion that they play a significant role in the rate of corrosion.

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Chapter 1- Introduction

Concrete and grout have many applications in today's world; they are used in the construction of roads, buildings, bridges, and dams to name a few. Concrete consists of portland cement, water, fine aggregate, coarse aggregate, and potentially mineral or chemical admixtures. Grout consists of only Portland cement, water, and potentially mineral or chemical admixtures; typically no aggregate is present though some grouts may contain finely ground fillers. In post-tensioned structures, grout is used primarily to protect reinforcing steel from corroding. In this experiment, pretension/post-tensioned bridge tendons are specifically analyzed. The focus of this study is to determine the cause of corrosion of steel tendons that are exposed to grout which contain different levels of chlorides.

One of the most important properties of concrete and grout is its ability to protect the structural steel that is essential to post-tensioned concrete. Grout is an excellent protecting agent because the high pH level of the grout allows for the formation of tightly adhering film which passivates the steel and protects it from corrosion. The addition of admixtures also allows for a low permeability that minimizes the penetration of corrosion-inducing substances. Low permeability also increases the electrical resistivity of concrete which hinders the flow of electrochemical corrosion currents. With these attributes of grout, significant corrosion of pre-stressing steel does not occur in the majority of post-tensioned structures. However, corrosion of the steel can occur if the grout is not of adequate quality, poor construction practices were used, the structure was

not properly designed for the service environment, or the environment was not as anticipated for changes during the service life of the concrete.

The corrosion of steel in concrete has increasingly raised attention in recent years due to its widespread occurrence in certain types of structures as well as the high cost of repairs.

Corrosion of steel reinforcement was first noticed in marine structures and in manufacturing plants. However, corrosion has become more noticeable on bridge decks, parking structures, and other structures as the use of chlorides increased, primarily as road salt to create safe driving conditions when roads are exposed to snow or ice.

Chloride ions are considered to be the major cause of premature corrosion of steel reinforcement. A high enough concentration of chloride ions will break down the passive layer, allowing the steel to corrode even in a high pH environment. Chloride ions are common in nature and small amounts are often present in the mix ingredients. However, specifications limit the amount of chlorides that can be present in both concrete and grout.

The rate of corrosion of steel reinforcement embedded in concrete is strongly influenced by the environment around the structure. Humidity (the moisture content in the air) is a prevalent factor when designing a structure. Along with oxygen, water is necessary for electrochemical corrosion to take place. With the addition of humidity to a chloride enriched environment, corrosion can be noticed in as little as a month.

The purpose of this report is to determine the effect of various concentrations of chloride ions on the long term durability of prestressing strands embedded in grout. To achieve this objective, samples were created to mimic portions of a post-tensioned duct. Each

duct was given a unique combination of chloride and water to create an ideal environment for corrosion to take place. More detail of the testing procedure will be explained in Chapter 3.

Chapter 2 - Literature Review

2.1 - General Corrosion

Since reinforced concrete was developed in the 19th century and prestressed concrete was developed in the 20th century, man has had to deal with a form of deterioration of steel and iron. At an estimated US \$2.2 trillion, the international annual cost of corrosion is a leading contributor to the deterioration of infrastructure. Yet governments and industries pay little attention unless in high-risk areas such as aircraft and pipelines [4].

Many think of corrosion happening to metals that are exposed to the elements that are on the exterior of structures and are visible. Corrosion does in fact happen to exposed metal rapidly, but corrosion can occur to metals that are embedded in concrete or grout. The research on uniform chloride levels reacting to embedded metals is very limited as the majority of research has focused on chlorides resulting from ingress from the environment, which leads to variations in the chloride concentration throughout the material. Metals that are covered by concrete, such as rebar or prestressing strand, can have large corrosive consequences when they are attacked by chloride ions. Corrosion of reinforcing in concrete or grout can reduce the structures overall capacity to support its designed loads and shorten the service life of the structure.

Put in place by the American Concrete Institute, chloride limits were implemented into mix designs to control the risk of corrosion happening to embedded metals in concrete. From ACI 318-08, Section 4.4.1; the chloride limits for new construction are detailed, for prestressed concrete with a water soluble chloride, the limit is 0.06 percent by mass. This

amount of chlorides is a conservative maximum amount to ensure as little corrosion as possible for prestressed concrete structures. Corrosion is the decaying and destruction of a material caused by the environment in which the material is placed in. Corrosion is a natural process that cannot be prevented, but the onset of corrosion can be delayed and the rate of corrosion reduced with correct measures. There are many forms of corrosion: uniform corrosion, galvanic corrosion, pitting corrosion, stress corrosion cracking, corrosion fatigue, intergranular corrosion, crevice corrosion, and erosion corrosion.

2.1.1 - Uniform Corrosion

Uniform Corrosion, also known as General Corrosion, is one of the most common types of corrosion. It damages the entire surface of the material at a constant rate which causes the material to become thinner. This chemical attack is easily identified by its appearance. However, if not controlled, the metal surface will continue to thin until there is nothing left [8]. Figure 1 is a picture of a sample that has undergone Uniform Corrosion



Figure 1: Example of Uniform Corrosion [8]

2.1.2 - Galvanic Corrosion

The second type of corrosion, Galvanic Corrosion, occurs in the presence of an electrolyte such as seawater when dissimilar metals are joined together; this can be seen in Figure 2. When a galvanic couple forms, one of the metals in the couple becomes the anode and corrodes faster than it would have if it were by itself, while the other metal becomes the cathode and corrodes slower than it would have if it were alone. For galvanic corrosion to occur, three conditions must be present: electrochemically dissimilar metals must be present, metals must be in electrical contact, and the metals must be exposed to an electrolyte [8].



Figure 2: Example of Galvanic Corrosion [7]

2.1.3 - Pitting Corrosion

Pitting Corrosion causes damage by randomly attacking a limited section of the metal's surface, leaving behind holes that are larger in depth than in width. This corrosion process typically starts in a scratch or nick that is deeper than any protective layer that was applied to the metal. As the process progresses, the metal becomes thinner and

weaker and can lead to stress corrosion cracking which begins at the base of the corrosion pits [7]. Figure 3 depicts a sample that is suffering from pitting corrosion.



Figure 3: Example of Pitting Corrosion [7]

Pitting corrosion is often a large concern for prestressing tendons because the resulting pits reduce the cross-sectional area of the tendons and produce stress concentrations. This can lead to brittle fracture of individual wires in a tendon and ultimately, the failure of the tendon and prestressed concrete member.

2.1.4 - Stress Corrosion Cracking

Stress Corrosion Cracking is a complex form of corrosion that occurs when brittle, dry cracks develop from the combined effects of a tensile stress along with a corrosive environment. Due to the difficulty in identifying the fine cracks where stress corrosion cracking can occur, engineers class stress corrosion cracking as a catastrophic form of corrosion. The damage cannot be predicted and inspectors often underestimate this form

of corrosion [8]. Figure 4 is a microscopic look at a specimen that is undergoing stress corrosion cracking.

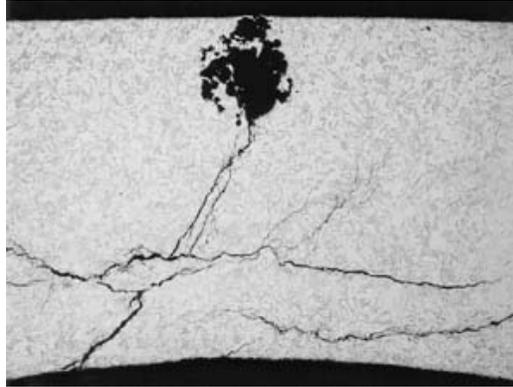


Figure 4: Example of Stress Corrosion Cracking [8]

These catastrophic cracks that cause the steel to fail at stresses below the yield stress can also be created by hydrogen embrittlement. Hydrogen embrittlement occurs in a number of forms, but the common features are an applied tensile stress and hydrogen dissolved in the metal. Currently, this phenomenon is not completely understood and hydrogen embrittlement detection seems to be one of the most difficult aspects of the problem. Hydrogen embrittlement does not affect all metallic materials equally; the most vulnerable are high-strength steels, titanium alloys, and aluminum alloys [8].

2.1.5 - Corrosion Fatigue

Corrosion Fatigue is the process of metal cracking below its tensile strength while residing in a corrosive environment. Inspectors have a difficult time detecting corrosion fatigue because like stress corrosion cracking, the cracks can be very fine and difficult to notice. Figure 5 depicts a microscopic look at a specimen suffering corrosion fatigue. If not detected, corrosion fatigue can be catastrophic. To prevent corrosion fatigue, it

requires designing and constructing the materials properly, reducing any stress locations, and removing any environmental contributors such as oxygen and hydrochlorides [7].

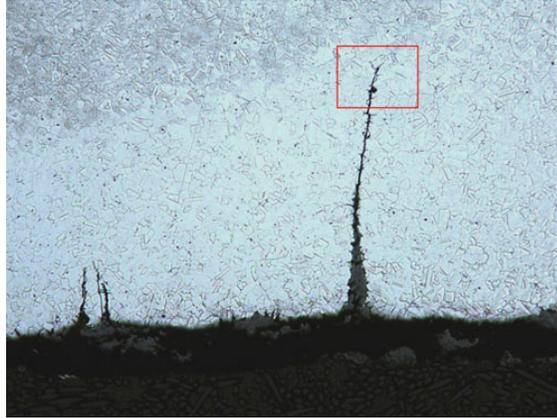


Figure 5: Example of Corrosion Fatigue [8]

2.1.6 - Intergranular Corrosion

Intergranular Corrosion occurs on or next to grain boundaries of a metal. The microstructure of metals and alloys consists of a granular composition. These grains are small crystals whose edges join the edges of other grains to form grain boundaries. This type of corrosion results in a loss of strength in metal parts where the grains have fallen out [8]. Figure 6 illustrates the cross boundary corrosion that takes place.

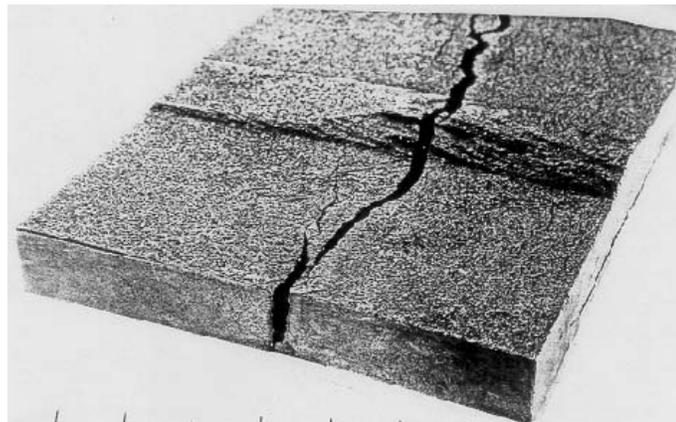


Figure 6: Example of Intergranular Corrosion [7]

2.1.7 - Crevice Corrosion

Crevice Corrosion, also known as concentration cell corrosion, forms when a liquid corrosive is trapped in a narrow gap between metals or between a nonmetal and a metal. Aggressive ions such as chlorides must be present in the electrolyte in order to fully corrode and become aggressive. Crevice corrosion develops quite similar to pitting corrosion, after the initiation stage, with a gradual decrease of the pH and in increase of chloride concentration within the crevice [8]. Figure 7 shows a common place for crevice corrosion. Many structures with channels and pockets develop crevice corrosion rather rapidly when in a corrosive environment.

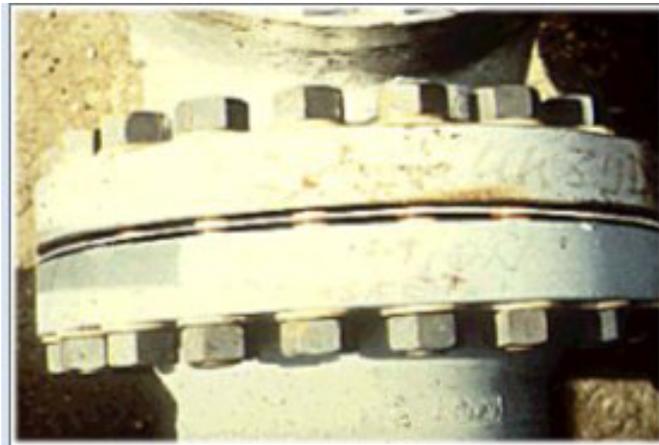


Figure 7: Example of Crevice Corrosion [8]

2.1.8 - Erosion Corrosion

Erosion corrosion is the process of a moving corrosive liquid on a metal surface, which leads to the accelerated loss of material. This type of corrosion is more common in soft alloys. Methods of controlling this corrosion include the use of harder or more corrosion-resistant alloys or adjustments in fluid velocity and changes in flow patterns [9]. Figure 8

illustrates the process of how the moving liquid disrupts the surface of the metal and creates a pit that expands as liquid continues to move across the metal.

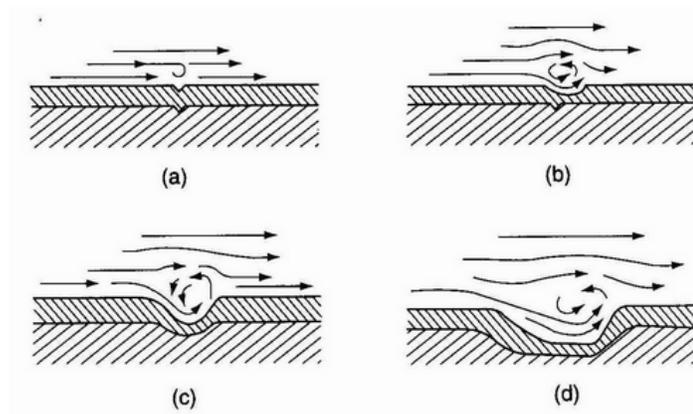


Figure 8: Schematic of turbulent eddy mechanism for downstream undercutting of erosion corrosion [8]

Figure 9 is a microscopic picture taken of a soft metal when it had been submerged in a flowing corrosive liquid. The picture clearly illustrates the individual teardrop shaped pits with undercutting in downstream direction.

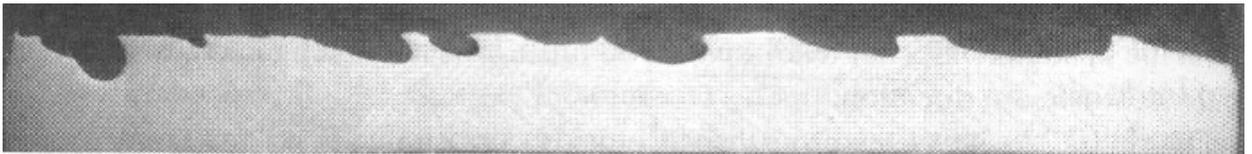


Figure 9: Photograph of erosion corrosion [9]

2.2 - Corrosion in Reinforcing Steel

In new structures with good-quality concrete, the concrete can protect the steel reinforcing bars from corrosion. For reinforcing steel that is in good-quality concrete, meaning concrete that contains minimal chlorides, is uncarbonated, and un-cracked, the steel is protected and no corrosion, or a corrosion rate which is very small, can be expected [5]. However, the concrete quality can be violated by either chemical or

mechanical means. Chemical means are chloride diffusion and carbonation, and the primary mechanical means is cracking. These cracks in the concrete allow water to pass through the protective concrete barrier and reach the steel bringing chlorides and oxygen which increases the corrosion process on the reinforcing steel [7].

The key to long term durability of reinforced concrete structures is the use of portland cement concrete with low permeability and adequate concrete cover. In order to resist chloride ion penetration or diffusion, a concrete with lower permeability is the best solution. This keeps chlorides, water, and oxygen from reaching the steel reinforcing bars. While an adequate concrete cover creates a larger barrier and demands more time for water and chlorides to make its way to the steel [5].

There are other factors that can help protect the steel from corrosion, such as: the water-cement ratio, admixtures, and cement type. Lower water-cement ratios generally make concrete less permeable [2]. Although a low water-cement ratio does not always guarantee a low permeable mix, concrete with the proper gradation and type of coarse and fine aggregates and mineral admixtures that have a high resistance to chlorides tend to have a lower water-cement ratio. According to “Materials and Methods for Corrosion Control of Reinforced and Prestressed Concrete Structures in New Construction”, a paper from the US Department of Transportation, the electrical resistance of concrete at 28 days and with water-cement ratios varying from 0.30 to 0.50 have been shown in tests to be similar, but are drastically altered at 90 days. The improved performance of concrete with lower water cement ratio is due to a reduction in concrete permeability and an increase of

resistivity. The resistivity of concrete with water-cement ratio of 0.30 is much higher than the resistivity of concrete with a water-cement ratio of 0.40 to 0.50 at 90 days [5].

Mineral admixtures can also be used in corrosion-control to reduce the permeability of the concrete. Some common admixtures used today are: fly ash, blast-furnace slag, and silica fume. These mineral admixtures reduce the permeability by increasing the formation of calcium silicate hydrate within the cement matrix. However, all admixtures must be evaluated for changes in their chemistry. Any changes can severely affect the characteristics of the concrete and possibly its performance [7].

Silica Fume is a byproduct of silicon metal and ferrosilicon alloy production. Silica Fume consists of very fine glassy spheres that allow it to fit into the small spaces that are usually occupied by water, creating a denser mix. This denser mix gives a compressive strength higher than those mixes without the admixture. Concrete mixes that contain Silica Fume are highly impermeable to chloride penetration and are resistant to the flow of corrosion currents due to their high electrical resistivity. Although silica fume has been shown to offer the largest and most consistent reduction in penetration rates for chloride ions in concrete, they are more susceptible to cracking [7].

The chemical composition of the portland cement being used also can affect the diffusion rate of the chloride ions. It is thought that one of the main mechanisms this is accomplished is through chloride binding. Chloride binding is the chemical reaction between chloride ions in a solution and the cement hydration products. This reaction produces calcium chloro-aluminates, which is an insoluble chloride phase. This insoluble

phase removes chlorides from the pore water and reduces the amount of free chlorides that are available to become part of the corrosion process [5].

2.3 - Corrosion in Prestressing Steel

In prestressed concrete structures, high-strength prestressing steel is used to increase load capacity, improve crack control, and allow the construction of more slender components. In pre-tensioned concrete, the tendons are tensioned before the concrete is placed around the strands and the concrete has cured. After the predetermined strength is reached with the concrete cured around it, the tendons are released which puts the concrete into compression. In post-tensioned concrete, the prestressing strands are placed in a duct which runs through the hardened concrete section. The strands are then stressed, placing the concrete in compression. The result of both processes is a higher quality concrete section that can support a larger load.

There are two main types of corrosion that happens to prestressed strands are pitting corrosion, and stress corrosion cracking. As described earlier, pitting corrosion is a localized galvanic corrosion cell that forms at weak points in the strand's protective system. Pitting corrosion arises especially in places where the protective metal layer has been damaged locally by aggressive chloride ions such as road salts. Pitting corrosion is more of a concern than general corrosion on prestressing steel since the loss of cross-sectional area can be quite high in localized areas along the prestressing strand. Stress corrosion cracking is when corrosion of the prestressing steel along with the high tensile stresses in the prestressing steel lead to cracking perpendicular to the direction of the applied stress.

The main causes of failure for prestressing steel in post-tensioned bridges are the corrosion of the steel tendons, deterioration of the protective ducts, and end anchorage failures which release all of the prestressed tendon capacity [5]. Corrosion of the tendons is a serious problem in many environments. The tendons are protected by a duct of usually corrugated piping or a plastic substitute. To ensure protection of the tendons, grout is pumped into the duct to completely cover the strands to protect from water, chlorides, and oxygen. Corrosion of the tendons are usually due to: voids under or next to tendons, lack of passivation of the tendons due to a decrease in alkalinity, corrosive environment, joints not sealed watertight, chlorides from the mix water or aggregates, inadequate concrete cover due to poor construction practices, or concrete with a high permeability due to a high water-cement ratio and/or poor consolidation.

There are some corrosion-protection measures that can be applied directly to the tendons. Epoxy coated strands are coated with epoxy that is able to accommodate the elongation of the strand when it is put into tension. This epoxy also comes equipped with a coarse grit embedded into the epoxy to aid the grout and tendon in bonding. This epoxy coat provides a moisture barrier that will aid the grout from keeping chloride contaminated water from entering the strand. Another protective measure that is incorporated is making the structure continuous for live load to minimize on joints that becomes a weak point on letting water in.

Failures of corrosion-protection systems for bonded post-tensioned concrete structures are commonly due to ineffective grouting materials and methods, poor workmanship,

construction defects, and poor design details. Poor design details provide easy access for chloride contaminated water to reach the tendons.

Chapter 3 – Design Parameters

3.1 - Introduction

Corrosion is a chemical reaction that takes place on the steel largely in the presence of chlorides. Corrosion is very highly variable because it is affected by multiple factors such as imperfections in the steel, imperfections in the grout, and the presence of oxygen and moisture. To adequately obtain enough data to make possible conclusions based by these multiple factors, many specimens were needed to be able to draw reasonable conclusions. In completion, over 300 samples were made. Within these samples, there were many variables that were implemented. These variables were: voided, not voided, repaired, amount of chlorides, amount of water mixed with the grout, and if it was drilled with a hole to allow for ventilation.

3.2 - Design Variables

In total, there were 312 samples that varied in amounts of chloride, water, pipe configuration, and amount of oxygen. Chlorides was a major variable in testing corrosion, therefore, there was 9 different chloride levels that were tested. The different chloride levels while using Sodium Chloride (NaCl) and assuming a 60% initial chloride content were:

- 0.04% acid soluble by weight of cement (fresh grout control)
- 0.2% acid soluble by weight of cement
- 0.4% acid soluble by weight of cement
- 0.6% acid soluble by weight of cement

- 0.65% acid soluble by weight of cement
- 0.75% acid soluble by weight of cement
- 0.85% acid soluble by weight of cement
- 1.0% acid soluble by weight of cement
- 1.5% acid soluble by weight of cement

All of the samples were made in two different batches. The first batch consisted of 222 samples that tested 0.04%, 0.2%, 0.4%, 0.6%, and 1.0% acid soluble chloride by weight of cement were cast in August 2011. It wasn't until March 2012 that 23 samples were sent to New Jersey for further testing and the second batch was mixed which added 105 new samples that were mixed with 0.40%, 0.65%, 0.75%, 0.85%, 1%, and 1.5% acid soluble chloride by weight of grout to further explore that window of percentages.

Water content was another variable that changed in the samples; for the grout that was tested, the recommended dosage was 11.5 – 13 pints of water per pre-packaged bag of grout. The different water contents that were tested were 11.5 pints, 13 pints, and 14 pints of water. 14 pints was included because it was thought that additional water (larger water to cement ratio) would increase the likelihood of corrosion and therefore this would provide a level of safety.

The last variables that were tested dealt with changes to the PVC tube as well as the configuration of grout. The changes made to the PVC tube were to increase the amount of oxygen that would be allowed to the sample. Some of the samples were sealed which gave the specimen a limited amount of oxygen. While other samples had a 1/8 inch hole drilled into PVC tube approximately 3 inches from the top.

The configuration of the grout was the last variable to be tested. There were three scenarios that were tested; solid, voided, and repaired. A solid specimen would be filled with grout to a certain height in one single pour. The voided specimens were filled with grout to a level that was 3 inches from the top. Repaired (Patched) specimens were filled with grout to the same level as the voided specimens. However, once the grout had cured, they were filled the rest of the way up with a non-chloride grout to investigate gradient concerns. Figure 10 illustrates the configuration of the samples with indications of the grout fill levels, and the drilled hole location (oxygen source).

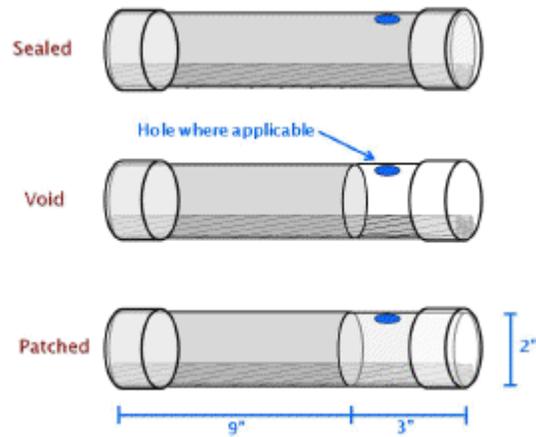


Figure 10: Schematic of Grout Samples

In order to know which sample was which, there had to be a naming system. An example of a specimen name is: V-S-.04-11.5-A. To identify if a specimen was voided, solid, or repaired, there had to be an initial. Therefore, “V” stood for void, “F” for solid/full, and “R” for repaired. The next letter in the title was to identify if the specimen was sealed which was represented with “S”, or if there was a hole drilled into the side of the PVC which was represented with “H”. The first number set in the title is to identify the chloride content in the specimen. In this example, there are .04% chlorides. The second

set of numbers in the title is to describe the water content. In this example, there is 11.5 pints of water that was mixed in the batch. The final letter in the naming scheme is to identify which of the three identical specimens this one is. For this example, this specimen is A.

3.3 - Design Process

To be able to compare specimens, the testing tubes had to be clear and manageable. In order to keep them this way, they were built out of clear PVC piping. Clear PVC piping would allow us to be able to inspect each sample monthly along with creating no unwanted reactions with the excess chlorides or steel. Each tube comprised of a 1 foot long, 2 inch diameter piece of PVC. These samples were then capped at one end. Once this was completed, three ½ inch prestressing strand were cut to 10.5 inches long and placed inside the tube. During the first batch of samples there was no preparation other than cutting the prestressing strand and placing them directly into the tubes. However, during the second batch of samples that were created in March 2012, the prestressing strands were wiped with acetone to remove any residual oil and dirt before being placed into the tubes that were now ready to be filled with grout.

This prepackaged grout that was used was a non-shrink, cementitious grout with a unique 2 stage shrinkage compensating mechanism. The typical use for this grout is for grouting of horizontal and vertical ducts within bonded, post-tensioned structures. It is also used to grout and fill or repair voids within ducts of post-tensioning strand for corrosion protection.

The mixing process that was used to fill the tubes was done by a hand mixer. This would allow the grout to be mixed in small quantities to accommodate the many variables. Each mix was put through a series of quality control tests to be able to compare mixes. A Mud Balance Test was done in accordance to American Society for Testing and Materials (ASTM) test number D2419 in order to get the fluid density of the mix. Mud Balance Testing ensures that grouts with the desired water to cement ratio are mixed. The next test that was done was a Flow Cone Test (ASTM #C939). Each mix was put through a Flow Cone Test to measure the fluidity of the grout mix. The final quality control test that was conducted on each sample was a Schupack Pressure Test (ASTM #C1741). This test applied a pressure to the grout for 10 minutes. While there was pressure being applied to the grout, water would segregate from the grout. This test determined the susceptibility of the grout to bleed.

3.4 - Batching Procedure

The procedure of batching was simple. First a half bag (11.35 kg) or three quarter bag (17.025 kg) of prepackaged grout was measured. The batch size varied due to the number of samples that needed to be made with particular water to cement ratio, and needed chlorides content (15 different combinations of chlorides and water). Next, the appropriate weight of chlorides (NaCl) was measured out; for the first batch of samples the chlorides were mixed with the weighted grout product and mixed with a paddle while still in dry form. Once the chlorides and grout were mixed together, the appropriate amount of water was measured out and added to the mix. In the second batch of samples, the chlorides were mixed into the water which was then mixed with the grout separately.

All mixing was done using the same lab equipment throughout procedure and was properly cleaned between all batches.

All the mixing was done in a 5 gallon bucket with a 2500 rpm drill. The drill was running at full speed during the mixing portion. The blade that was used can be seen in Figure 11.

This blade was 3.5 inch high shear paddle that was attached to the drill.



Figure 11: Shear Paddle Mixer Used

The prepackaged grout was then slowly added to the water while the drill mixer was running at an approximate half speed. Once all the prepackaged grout was added to water, drill speed was increased to full speed (2500 rpm), and the stopwatch timer was started; after five minutes of mixing, the grout was distributed into the PVC tubes. At this time quality control testing was done to determine comparable properties of the different mixes. Finally, the grout was poured into the PVC testing tubes and was immediately capped. For the first batch of samples, wet rags were placed on top of the holding boards, and a plastic sheet was used to cover the samples. All casting for the first batch of samples were performed on July 26th and 27th of 2011. Samples were cured at room temperature (approximately 72 degrees Fahrenheit) until they were put into the humidity

controlled chamber on August 6th, 2011. The samples that needed the repair patch had additional grout added to samples on August 2, 2011. The same procedure was used as stated earlier without the addition of chlorides to the grout mix. The second set of samples was cast on March 27, 2012. All samples were cured at room temperature for 7 days when they were placed in the humidity controlled chamber.

3.5 - Environmental Conditions

All of the samples that were created were stored inside a “controlled environment” that was created by a humidity chamber. All of the samples were placed inside the chamber within two weeks of casting. There were two chambers that were used; the first was a more temporary chamber while the second one that was built was intended to be used for a long period of time. When the temporary chamber was being used, relative humidity was approximately 65% and the room temperature was approximately 72 degrees Fahrenheit. This chamber can be seen in Figure 12; it consisted of a wooden frame with plastic sheathing for walls. The humidity was supplied by a standard commercially available wick humidifier.



Figure 12: Initial Environmental Chamber

On December 28th, 2011 the chamber was updated to allow for higher temperature and humidity. The modified chamber consisted of foil back foam insulation paneling on a wooden support structure as shown in Figure 13. The renovated chamber also included electronically controlled temperature and humidity, with the target values of 80 degrees Fahrenheit and 85% relative humidity. The humidity is controlled through the use of a submerged heating element.



Figure 13: Updated Environmental Chamber

On January 25th, 2012 two temperature and humidity sensors were added to the chamber. These are remotely monitored and record temperature and humidity at specified intervals. One sensor is in the South West corner of the chamber approximately 30 inches above the floor; the other sensor is approximately 45 inches above the floor.

3.6 - Inspection Procedure

Each month, all the samples are inspected for cracking, strand condition, and any corrosion that has occurred. All the inspections were done using an Inspection Protocol.

The steps that were taken for inspection are as follows:

1. Remove rack from storage.
2. Verify sample identification information with data recording sheet.
3. (First Inspection only) Mark the 0° , 120° , and 240° azimuths on the sides of the pipe just below the cap with a paint marker. Mark azimuth 0° at the leftmost strand with viewed from above.
4. Observe the face of the sample between azimuth 0° and 120° and document all observations, recording azimuth and distance from the bottom of the sample. Sketch any anomalies on Inspection Sheet and photograph. Save anomalies on the attached photo sheet (re-label page to match sample number) and print for record with Inspection Sheet.
5. Photograph the overall face with a label identifying the sample, azimuth markings, and a ruler all clearly.
6. Rotate the sample 120° and repeat steps 4 & 5 for the 120° to 240° face.
7. Rotate the sample 120° and repeat steps 4 & 5 for the 240° to 360° face.
8. Remove end cap briefly to observe end condition of any exposed strands and document. Rate steel condition from “1” to “8” in accordance with photographs provided. Identify strands as “A”, “B”, and “C”. Photograph the condition of the exposed strands.

9. (First Inspection only, for “solid” and “repair” samples only), use a wire brush to remove loose material at exposed strands and pack ends with petroleum jelly, ensuring that all exposed steel is coated.
10. Photograph any features of note with a special photograph.
11. Recap the sample and replace in chamber.
12. Store all photographs in a structured directory to allow them to be located for future comparisons.

Figure 14 illustrates a typical sample and the proper markings. The azimuth markings are for ease of direction on where cracks and corrosion stains are in relation to the strand.

With the leftmost strand located at the 0° mark.



Figure 14: Typical Test Tube Azimuths

During inspection it was important to not only look at the outside for noticeable cracking and corrosion stains, but to check the strand conditions of the strand on top. Some of the strands were more exposed compared to others because of different filling levels of grout. Starting on the first inspection, all of the specimens were evaluated with three numbers that ranged from 1 to 8; each number corresponded with a rating for each of the three

strands in the specimen. Appendix section 7.1 includes the steel condition rating images that were used to compare the strands to in order to get a rating of 1 through 8; 1 representing no corrosion and 8 representing severe corrosion. Once the strands had been rated, it was important to apply petroleum jelly to the specimens that were “solid” and “repaired” to ensure that further corrosion of the strand would not happen. This procedure of applying petroleum jelly was only conducted to the first batch of specimens. The second batch of specimens did not require the addition of petroleum jelly because they were cast with the strands fully incased in grout for the fully grouted samples. After each inspection, a monthly report was put together that stated which specimens were seeing cracks and corrosion. The first 5 monthly inspection reports can be referenced in section 7.2 through 7.6 of the Appendix.

Chapter 4 – Experimental Results

The results for this report were gathered over a five month period. During those five months, the samples were stored inside the permanent environmental chamber. Once a month, all of the samples were inspected using the process described in Section 3.6. During inspection, all corrosion stains, cracks and strand conditions were noted as well as photographed for future reference.

This chapter explains and illustrates the corrosion progression that happened within the samples. It starts with the summary of the first inspection, explaining each month's inspection chronologically to find patterns, and concludes with a summary of inspections.

4.1 - January 2012 Inspection

The first inspection was conducted on January 27th, 2012. During this inspection there were only 6 specimens that had noticeable corrosion stains on the grout. All 6 of these specimens contained the higher chloride amounts in the testing program. Five of the six specimens had the highest chloride level of 1%, and the sixth had the second highest chloride level of 0.6%. At this time, only the first set of samples had been created and was inspected. The majority of the corrosion seemed to occur where the strand was in contact with the plastic tube, and there was a void in the grout.

The specimen that showed the most corrosion was sample R-H-1.0-11.5-B, which stood for repaired – drilled with hole – 1.0% chloride content – mixed with 11.5 pints of

water – sample B. Figure 15 illustrates the corrosion stain that was observed during the inspection. This specimen contained the largest amount of chlorides that were tested along with the least amount of water that was mixed in the batch. This specimen had a stain that measured 4 centimeter long and 1 centimeter wide and was located where the strand was in contact with the plastic tube. As was common in the other specimens, this stain was located about 1/3 the way down from the top.

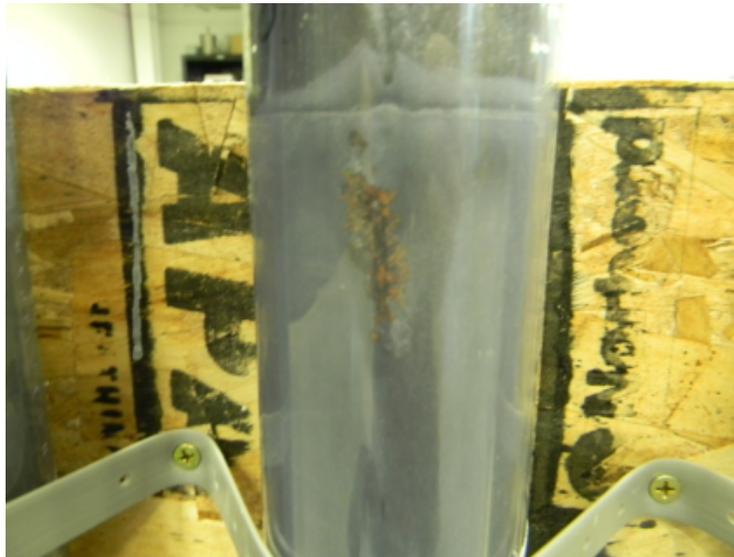


Figure 15: Specimen R-H-1.0-11.5-B

Along with checking for corrosion stains, specimens were inspected for cracks. In total, eight specimens suffered visible cracks that were measured and photographed. Seven of the eight cracks observed were believed to be shrinkage cracks, because the cracks were horizontal cracks, about 0.25 centimeters below the surface of the grout. Comparing all of the cracks, they all had a similar length of 7 centimeters long. The January Report can be referenced in section 7.2 of the appendix. Within this report, there is a short

description and pictures of all the stains and cracks that were observed during this inspection period.

4.2 - February 2012 Inspection

February 24th, 2012 was the date of the second inspection on all of the specimens inside the humid chamber. This inspection found five new corrosion stains and two new cracks. The new stains that were observed all happened on samples with 1.0% chlorides. However, instead of being similar to the January inspection, four of the five new corrosion stains occurred in higher water contents. Two of the new specimens were mixed with 13 pints of water, and two specimens were mixed with 14 pints of water. Specimen F-H-1.0-14-B (which is solid, has a drilled hole, 1.0% chloride, and 14 pints/bag of water) is one of the specimens that suffered corrosion with the highest mixed water content. This stain was measured to be 2 centimeters wide by 2 centimeters long and occurred at the top of the specimen, near the three strands. This stain was surprising because it grew substantially in the small amount of time between inspections. One justification for the corrosion is a lack of Vaseline that was applied to this specific area. Figure 16 shows a dark gap of Vaseline that should have been covering the steel to stop the corrosion from happening around it.



Figure 16: Specimen F-H-1.0-14-B

The February inspection was also a time to observe how the previous corrosion stains were behaving. After observing all of the samples, it was noticed that none of the previously corroded stains from the January inspection had grown. However, one of the samples (F-H-1.0-11.5-B) that had a previous stain had developed a new stain near the original stain.

As stated before, there were also two new cracks that had developed in the specimens. One of these cracks occurred directly below three stains. Figure 17 is a picture of specimen R-S-1.0-11.5-C (repaired, sealed, 1.0% chloride, and 11.5 pints/bag of water) that was taken of the three stains as well as the cracking that occurred below the stains. These three, 1 centimeter by 1 centimeter blotches, were splitting the repair line. This is interesting because of the difference in grouts. As stated earlier, the “repaired” grout,

which is above the repair line, is a normally mixed grout with no added chlorides. While the grout below the repaired line is the grout with 1.0% chlorides and mixed with 11.5 pints of water.



Figure 17: Specimen R-S-1.0-11.5-C

The February Inspection report that explains all of the corrosion stains and cracks that were observed during this inspection can be referenced in the Appendix under section 7.3.

4.3 - March 2012 Inspection

Not only did an inspection occur on March 28th, 2012, but a second batch of 105 new specimens was added to the environmental chamber. These new samples were mixed, and

quality control tested during March 26th and March 27th. A week after the production and inspection of the new samples they were placed with the first batch of samples in the environmental chamber.

During the inspection of the first batch, there was an increase in observed cracks. Most of these cracks were minimal and were located near the free surface of some of the voided specimens. This is most likely indicative of shrinkage occurring on the top surface of the specimen. Figure 18 illustrates the cracking that was observed.



Figure 18: Typical horizontal crack 0.25 centimeters below surface

Upon inspecting previous samples that were showing corrosion, only two samples had made any types of changes. The largest change came from specimen F-H-1.0-14-C (solid, has a drilled hole, 1.0% chloride, and 14 pints/bag of water). This specimen's stain grew from $\frac{1}{2}$ cm x $\frac{1}{2}$ cm to $\frac{1}{2}$ cm x 2 $\frac{1}{2}$ cm. This growth was believed to have happened because of the location. The location of this stain was at the top of the specimen and was exposed to the air/humidity. Along with these two changed samples, corrosion was observed in six new specimens that had chloride levels ranging between 0.4% and 1.0%. Within these new specimens, four of the new specimen's corrosion stains were small $\frac{1}{2}$ cm x $\frac{1}{2}$ cm spots and were near the contact area of the strand and plastic tubing.

One of the new stains that were observed during this inspection was a little more interesting than the others. Specimen F-S-1.0-11.5-C (solid, sealed, 1.0% chloride and 11.5 pints/bag of water) had developed a stain that was near the strand location and was near the top. But, the notable characteristic of this stain was the crack that had developed with the stain. When corrosion occurs, the resulting material has a larger volume than the material consumed. This expansion creates tensile stresses in the concrete and causes cracks. This stain and crack were noted so that it could be determined if changes occur during the upcoming inspections, a picture of this specimen can be seen in Figure 19.



Figure 19: F-S-1.0-11.5-C

Section 7.4 of the appendix is the March Inspection report that contains all of the pictures and observed data that was recorded on March 28th, 2012.

4.4 - April 2012 Inspection

The April inspection was the first inspection that was conducted on the new samples that were created and placed into the environmental chamber in late March of 2012. The inspection on April 27th, 2012 saw the largest jump in corrosion stains of all the months of inspecting; there were 46 samples that showed new corrosion stains. When observing the month old samples, the majority of the stains were happening between the 0 and 120 degree markers. As stated previously, this is typically a surface-contact corrosion stain. A common stain that was occurring on the new specimens was a roughly 1-2 cm tall and 1 cm wide stain that was orientated just to the left of the 0 degree line. Figure 20 below illustrates how some of these stains were appearing. Another interesting relationship between these corrosion stains was the location vertically in the tube. Many of the new stains were occurring on the top half of the testing tubes. This was primarily due to the close proximity of the strand to the sidewall at the top and to the drilled hole in some of the samples.



Figure 20: Specimen - V-S-.85-13-C

Although many of these specimens were undergoing corrosion nearly in the same locations, there were a handful of specimens that were experiencing different rates of

corrosion. Specimen V-S-.85-13-B (voided, solid, 0.85% chlorides, 13 liters of water) was experiencing a much more rapid rate of corrosion. As figures 21 through 23 illustrate, this specimen had more than 3 corrosion stains. Figure 21 is a picture of the top portion of the specimen. Although it is difficult to see past the dried grout attached to the outside and the positioning of the glare from the flash; there lies a stain that measures to be 1cm x ½ cm. This stain is very similar to the stains that were recorded to the other specimens; it lies left of the 0 degree line, it lies within the top 4 cm of the top, and its shape is consistent with the other samples.



Figure 21: Specimen V-S-.85-13-B, Top portion of specimen

The second corrosion stain that occurred was the largest of the three stains. This stain measured to be 1.5 cm long and 1 cm wide. The stain location was expected when compared to other specimens. The stain occurred nearest to a strand, with the longest dimension of the stain along the direction of the strand. Figure 22 shows the stain. In this picture, it is clearly seen that there are two lighter colored grout channels. This differentiation in color on the grout is due to the strands being in such close proximity to the side of the container.



Figure 22: Specimen V-S-.85-13-B, Middle portion of specimen

Figure 23 illustrates a stain that was recorded due to the strand being close to the side wall of the tube near the bottom of the specimen. This stain which resembles a “frown face” was measured to be two $\frac{1}{4}$ cm dots and a $\frac{1}{2}$ cm long stain that was occurring on the opposite side of the strand. Again, in this figure the proximity of the strand to the sidewall of the tube can be seen in the light coloration of the grout. This condition represents a common situation in the field; whenever a post-tensioned duct deviates from linear, the strand will compress against the sidewall when it is tensioned.



Figure 23: Specimen V-S-.85-13-B, Bottom portion of specimen

4.5 - May 2012 Inspection

The May inspection occurred on May 29th, 2012. During this inspection there were only four new specimens that showed corrosion stains. All four were showing stains in roughly the same location, with all of the stains located between 2 cm and 4 cm from the top of the grout. This is interesting because it raises the question, “why in this particular location?” Upon further investigation into the specimens, all four were filled to the top; however, one was a repaired sample. Another similarity is that three of the four were all sealed; only one had a hole drilled into the side.

Looking further into these four samples, all three had roughly the same size of corrosion stain. Figure 24 illustrates one of these four samples. As it is clearly seen, the sample only experienced a small stain; it measured 1 cm in height and ½ cm in width. The black line that is just right of the corrosion stain is the zero degree line. This means that this stain, along with the other three new stains, were all next to the strands.



Figure 24: Specimen F-H-1.0-13-A-2

During the May inspection there was one specimen that showed significant growth in staining and required further investigation. Specimen F-S-1.0-11.5-B-2 (Full, Solid, 1%

chlorides, 11.5 pints of water) changed rapidly in the month since the previous inspection; it can be seen in Figure 25. This specimen is only two months old and during this inspection, had one new stain, a changed stain, an unchanged stain, and a growing crack.



Figure 25: Specimen F-S-1.0-11.5-B-2

The largest stain (the furthest right) measured at $1 \frac{1}{2}$ cm by 1 cm. This corrosion stain is a new stain for the specimen. It should be noted that the zero degree line, which is supposed to be on the edge of the strands, is not properly marked on this sample. For the second set of samples the strands were fully encased in grout and therefore it was very difficult to accurately determine the true location of the edge of the strands. The three stains shown correspond to the location of the three strands within the sample. The crack in the picture was an existing crack that changed since last inspected; however there was no stain at the end of it. This crack became a road for moisture and oxygen to travel and collect at the end of the crack which allowed the corrosion to propagate more quickly. The right stain and the middle stain were existing stains that were recorded in the April inspection. The middle stain that is just to the right of the black zero degree line is an unchanged stain that measures to be $1 \frac{1}{4}$ cm tall by $\frac{1}{2}$ cm wide stain that sits just below

the crack. The third stain changed since the months before inspection. This stain grew from 1 cm tall by $\frac{1}{2}$ cm wide to 1 cm tall by 1 cm wide. This specimen was, by far, the most active in change when compared to the rest of the samples.

Chapter 5 – Data Analysis

5.1 - Introduction

As described last chapter, there were many different corrosion stains that occurred over the specimens. There was a small rise in corrosion stains at the beginning of the experiment, while the number of specimens showing corrosion increased over time. With the addition of 105 new specimens in March 2012, there was a large spike in specimens showing signs of corrosion.

The data that was previously introduced in Chapter 4 will be analyzed in order to get a better understanding of the corrosion process for these samples. The analysis will focus on the physical changes to the specimens undergoing the different experimental variables as well as the trends that resulted because of the various specimen characteristics. The physical changes to the specimens will be analyzed to find corrosion and cracking trends that transpired over the months of inspecting. The many variables that were implemented into this experiment resulted in various forms of corrosion in the samples. This chapter will illustrate the trends as well provide explanations as to why these trends occur.

5.2 - Data Analysis

To fully understand the trends that developed over the 5 month experiment, it is important to know the percent of total specimens that showed signs of corrosion per month. As explained earlier, there was an initial batch of specimens that completed their first inspection in January 2012. A second batch of samples was cast in March 2012, and when these samples were first inspected in April there was a significant increase in percent of corroded specimens recorded. Due to the fact that there were two different batches at two different ages that were inspected each month, the graphs had to present the data by age to identify similarities. On all of the graphs that are presented, the horizontal axis of each graph is the inspections month. For the batches that were created in July of 2011, these samples were actually 6 months old by this point, but were undergoing their first month of inspections. While the second batch of specimens that were created in March of 2012 were truly only a month old and were undergoing their first month of inspections.

5.2.1 - Chloride Levels

In this experiment, there were seven levels of chlorides that were tested. Each level of chloride had multiple variables that were tested. Figure 26 illustrates the percent of specimens per chloride level that were showing signs of corrosion.

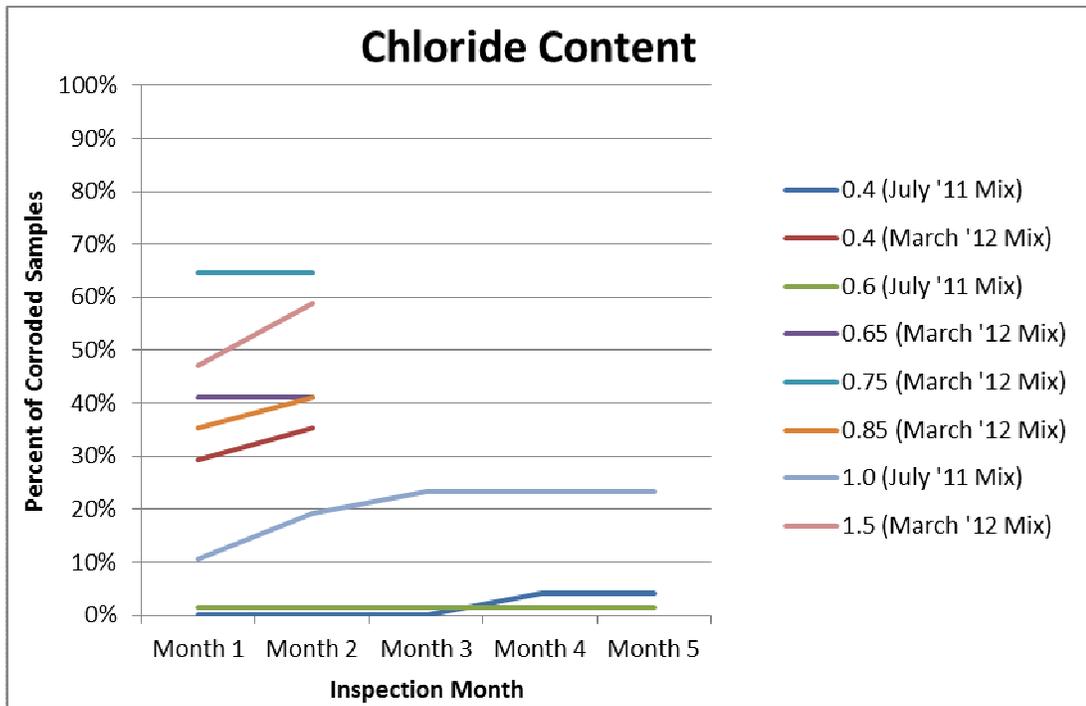


Figure 26: Percent of Corroded Samples Broken Down by Chloride Levels

All of the corrosion levels are not plotted due to the lack of corrosion in many of the lower chloride content samples. The vertical axis of the graph indicates the percent of corroded specimens that were showing corrosion out of the total number of samples that were tested with that chloride level. The horizontal axis is a measurement of what inspection the data is from. For example, month 1 indicates the first inspection that was conducted.

Reading from left to right on the graph, the growth of corrosion was close to what was expected. The higher quantity of chlorides in a sample would have more samples corrode compared to samples that were mixed with lower quantity of chlorides. It is important to remember that the samples that were created in March of 2012 were designed to replicate the worst case scenario in the field, the removal of the drawing oil from the surface of the

strand. It is apparent in the graph; all of the samples that were created in March 2012 have higher percentages than those created in July 2011.

Due to the fact that there is only two months of data on the new samples, it is difficult to make any real measure of which chloride level is creating the most corrosion. Using the data that is plotted, 0.75% acid soluble by weight of cement produces the highest corrosion rate, which is not expected. It would be expected that the higher chloride contents would show higher corrosion percentages. However, looking at the slope of the lines, we can predict which are showing increased signs of corrosion. As expected, samples that were mixed with 1.5% acid soluble by weight of cement were showing more corrosion at a higher rate by monthly inspection, but this observation is based on limited data and needs to be validated using additional data.

5.2.2 - Water Content

The amount of water used in this experiment was 11.5 pints, 13 pints, and 14 pints as discussed earlier. Figure 27 graphically represents the data that was collected. This data represents the percent of specimens that showed signs of corrosion that were mixed with the specific water content.

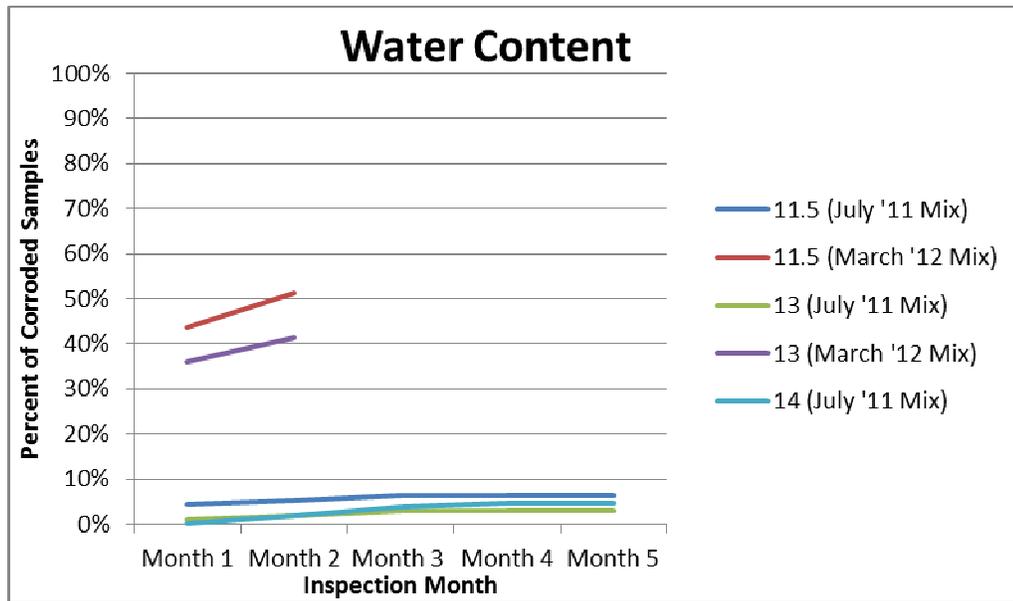


Figure 27: Water Content of Corroded Specimens

Figure 27 is difficult to read because when the new specimens were added in March, they were only mixed with 11.5 pints or 13 pints of water. As shown in the chloride content section, these samples had a higher percentage of corrosion when compared with the first set. When observing the batches that were created in July 2011, it is apparent that they all begin with similar slopes. For the first three months of the experiment all three variables had consistent and uniform slopes.

After the first two months of inspections, it was obvious that there was more corrosion happening to the samples that were mixed with 11.5 pints of water. One possible explanation is that the majority of observed corrosion is occurring where the strand is in close proximity to the tube sidewall. The likelihood of corrosion is increased in the presence of a small defect or void in the grout, and a grout with lower water content will have less fluidity and is therefore more likely to produce a defect. However, the difference between the various water contents is small, and within the standard variation

that is expected when conducting corrosion testing so it is difficult to make any definitive conclusions. The new specimens were tested with 11.5 pints and 13 pints of water because they were the minimum and maximum dosage of water recommended by the grout suppliers.

After the addition of the new specimens in March, the samples with 11.5 pints of water were still corroding at the highest rate; however, as with the previous set of difference was small and within the expected variation of the test. This reinforced the conclusion that was drawn from the initial set of data, that the water content does not significantly affect the rate of corrosion for these samples

5.2.3 - Specimen Characteristics

The testing program included two other variables related to the geometry of the specimen. Some of the samples were sealed, while others were exposed with a hole drilled into the PVC case. Additionally the grout within the sample was classified as either voided/filled to the top/or repaired by doing two separate pours. The samples had interesting results when broken down using these characteristics.

Changing the availability of oxygen allows for a comparison of real world situations where the strand is located in a well-constructed duct that is sealed from outside influence, and a duct that has defects that allow for more air flow through the duct. This test was conducted by drilling a hole into the wall of the tube to allow circulation of air to a portion of the sample. Comparisons were completed each month to determine which specimens underwent more corrosive changes. Figure 28 illustrates the data that was obtained.

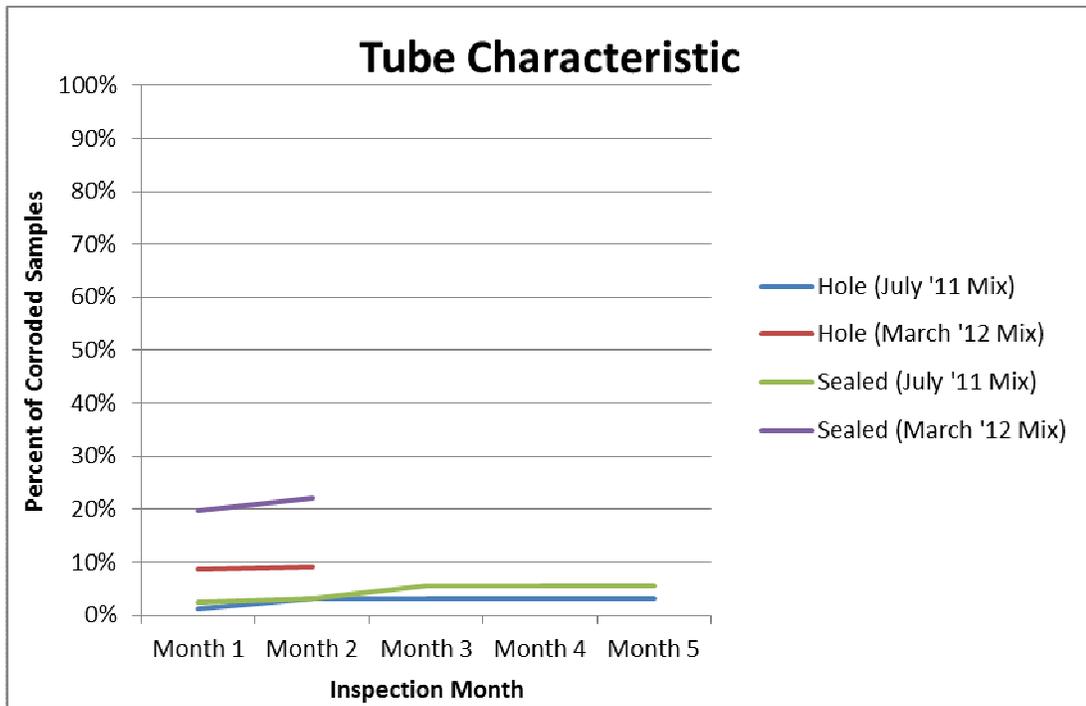


Figure 28: Test Tube Characteristics of Corroded Specimens

At first glance, it is noticeably similar to the graphs of water content and chloride amounts. However, it is interesting because between months 3 and 5, there were no new corroded samples recorded for specimens that had a drilled hole characteristic from the July 2011 mix. This may indicate that having a hole drilled into the side of the test tube did allow flow that prevented a pooling effect of moisture that would allow for increased corrosion rates. It can also be seen at the end of the graph when the number of corroded samples that were drilled with a hole only increased by a small percentage.

For both mixes that were completed, there was more corrosion in the samples that were sealed than those that were drilled with a hole to allow for air flow. However, there currently is not enough of a differential to suspect the tube characteristic a major contributor.

The second variable that dealt with specimen characteristics was how the specimen was prepared. There were three different scenarios that were tested to identify any trends in how the post-tensioned ducts would be filled. The three options, as discussed earlier, were full, repaired, or voided. The fully grouted samples were specimens that were filled up to the top on the day of mixing. The voided samples were specimens that were two-thirds filled to allow for more of the strands to be exposed to the humidity in the humid chamber. And finally, the repaired specimens were filled to the level that the voided samples were filled, allowed to cure, and later filled with a new chloride free mixture to the level of the full samples. Figure 29 is a graph depicting the data that was gathered of the number of corroded samples that were tested under each of the three characteristics.

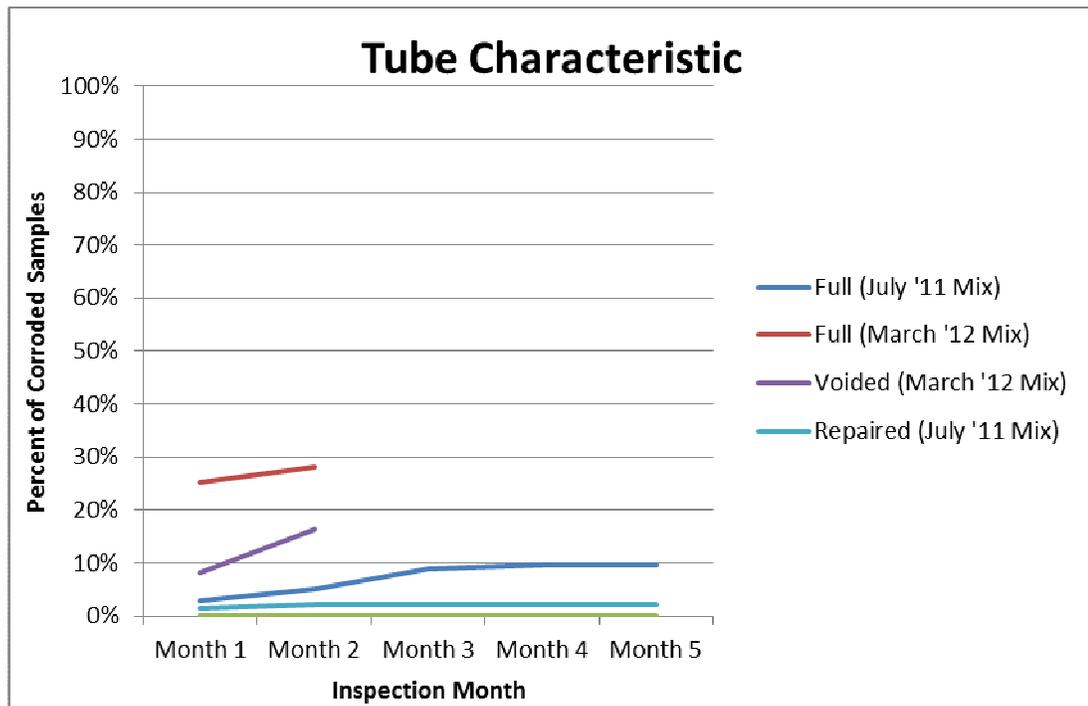


Figure29: Grout Level Characteristics of Corroded Specimens

Referring to Figure 29, the data that was gathered during the five months of research resulted in some interesting trends. One thing to note when analyzing the data is that when the new specimens were added in March, none of them were tested as being a repaired specimen. All of the new specimens were tested as full or voided.

Interestingly, there were zero specimens that were showing signs of corrosion for the first three months that were tested using a voided configuration. However, as soon as the new samples were created, there were over ten that were showing signs of corrosion as depicted by the “Voided (March ’12 Mix)” line. The reason why there were no samples that were showing any signs of corrosion for the voided July ’11 mix was due to the fact that all of the voided samples were tested with the lower amounts of chloride. There were no samples that were mixed with a higher percentage than 0.65% acid soluble by weight of cement. Once the new samples were introduced, they were mixed with higher percentages (0.75%, 0.85%, 1.0%, and 1.5% acid soluble by weight of cement) to increase the rate of corrosion in these samples.

Quickly looking at Figure 29, it is easily recognizable that the samples that were filled to the top of the testing tubes resulted in more corroded samples. The data shows that there was a steady increase in corroded samples during every inspection of samples that were filled and placed in the humid chamber. This may be due to the lack of higher chlorides in the first set had a void. It may also be due to the location of the strand within the grout. The way in which the samples were cast led to the strand being closest to the side of the sample at the top. In the majority of samples, this is where corrosion initiated, and the presence of a void at the top removes the opportunity for the corrosion being examined in

this study to occur. When evaluating all available data, it appears that there is not an increase in likelihood of corrosion in the presence of a void or repair.

5.3 – Conclusion

After analyzing the data graphically, it is easy to see trends which can lead us to predicting which specimens would corrode more rapidly. As discussed in this chapter, based upon the results of testing to date, a specimen that contains 0.75% acid soluble by weight of cement, mixed with the lowest recommended amount of water, 11.5 pints, had a sealed tube, and was filled completely on the day of mixing would most likely corrode. Although the data states that 11.5 pints of water would be the most likely to corrode, the variation is small and within the expectations of the test. This leads to the conclusion that water content is not a primary contributor to the likelihood of corrosion. A similar argument could also be made for the presence of a hole, and the configuration of the grout. Therefore, the only variable within this testing program that seems to have a significant effect on the corrosion rate is the chloride level. Based on the preliminary data presented, it appears that any level of chloride above 0.6% is at an increased risk of corrosion. However, it is unclear if this corrosion will continue to remain active, or if it is the result of surface corrosion that occurred before the steel had passivized.

Chapter 6 – Conclusion

After the review of all of the samples broken into the different characteristics that were tested, it became apparent on which parameter was dominant within each tested variable. The data proved to yield interesting results and when plotted, showed many noticeable trends that could be related between tested variables.

With the results of testing to date, it is clear that the amount of chloride is the only variable that was tested that had a significant effect on the rate of corrosion. The amount of water and characteristics of the specimen had a few trends but nothing that would lead to the conclusion that they play a significant role in the rate of corrosion. The preliminary data presented supports the claim that any level of chloride above 0.6% is at an increased risk of corrosion.

After collecting and analyzing the data, the preliminary recommendation would be to have a 0.6% acid soluble chloride by weight of cement as a maximum allowable chloride value. This level of chlorides proved to be highest level at which substantial corrosion did not initiate. Additional testing is required to see if this trend continues as the samples age. Additional samples may show corrosion, or the corrosion that has already occurred may shut down as the steel passivizes.

Based upon the research described, a few recommendations can be made regarding future research. First, further monitoring of these corrosion samples shall be done in order to obtain more data and determine longer effects of the chloride limits in the grout. Second, the apparent variation in initial corrosion between the two batches of samples could be

investigated. As described in Chapter 3, there were minor differences in the procedure when preparing the two batches including the strand preparation (acetone wipe or not) and the method of adding chlorides to the mixture. It was not anticipated that these procedural modification would significantly affect the results; however, there was a dramatic increase in corrosion in the second set of samples. The reason for this increase may provide a better understanding of the mechanisms behind the observed corrosion. The results from this study are very important when analyzing post-tensioned bridge tendons. Filled and sealed tubes are very common in today's practice during post-tensioning of concrete structures. Along with these common conditions, chlorides can be found in some tendons. The chlorides can be from the materials used, improper construction, or leaching of chlorides during service. The research described in this report provides some guidance on the implications of various chloride levels, which may be found in these tendons.

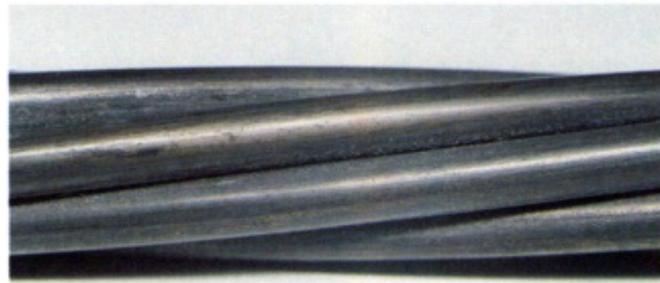
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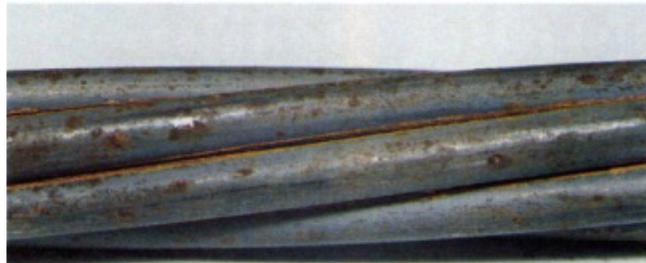
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Chapter 7 – Appendix

7.1 – Steel Condition Rating Images



1



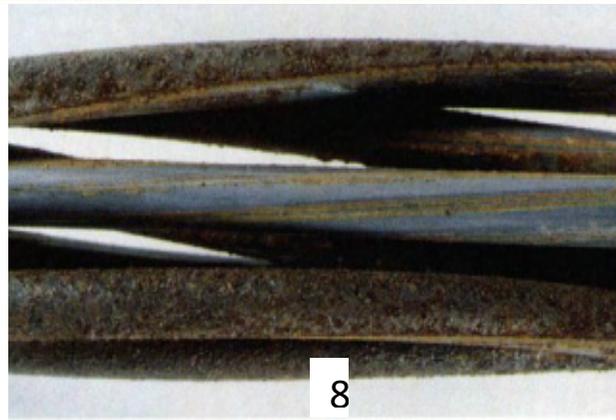
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7.2 - January 2012 Inspection Report

Title: Interim Report on Long Term Corrosion Testing at UMD

Date: February 18, 2012

Prepared by: Eric Musselman

Included in this report is a summary of the inspection of the long term corrosion specimens that was conducted on January 23-27, 2012. The inspection was completed by 2 graduate students at UMD: Ben Thiesse and Waylon Munch. At the time of inspection, the exposed strands of the unvoided specimens were sealed with petroleum jelly to prevent further corrosion of the exposed strands.

The results of the inspection are summarized in Tables 1 and 2 on the next page.

Minimal cracking was observed in the specimens, with the only crack occurring near the free surface of some of the voided specimens. This is most likely indicative of shrinkage occurring on the top surface of the specimen. Corrosion was observed in 6 different specimens, all with chloride levels of 0.6% or higher. The majority of the corrosion seems to be occurring where the strand was in contact with the plastic tube, and there is a void in the grout. However, in at least one of the specimens (R-S-1.0-11.5-C which is a repaired, sealed, 1.0% chloride with 11.5 pints/bag of water) the corrosion being observed seems to indicate corrosion occurring in a well grouted region (particularly around the repair). In addition to the tables summarizing the results, figures are included that show the typical cracking observed as well as the corrosion for the specimens in which it was observed.

Key to specimen labels:

V= Voided

S = Solid

R = Repaired

H = Hole

S= Sealed

.04, .2, .4, .6, 1 = Chloride Level

11.5, 13, 14 = Water content (pints/bag)

A,B,C = Specimen indicator

Table 1: Summary of Cracking Observed

Specimen	Location	Size
V-H-.04-14-A	From top at 45% angle	2 cm
V-H-.2-11.5-B	Horizontal approx 0.25 cm from top	6 cm
V-H-.2-11.5-C	Horizontal approx 0.25 cm from top	5.5 cm
V-S-.4-11.5-A	Horizontal approx 0.25 cm from top	8 cm
V-S-.4-11.5-B	Horizontal approx 0.25 cm from top	8 cm
V-H-.4-11.5-A	Horizontal approx 0.25 cm from top	6 cm
V-H-.4-11.5-B	Horizontal approx 0.25 cm from top	8 cm
V-H-.4-11.5-C	Horizontal approx 0.25 cm from top	7 cm

Table 2: Summary of Corrosion Observed

Specimen	Description	
F-S-.6-11.5-A	Two 1 cm long stains about 1/3 the way down from top	Figure 2
R-S-1.0-11.5-C	Two stains. The first stain is a 2 cm long stain by ½ cm wide about a third of the way up from the bottom. The second stain was a series of three small blotches that sat on the "Repair Line". Each blotch was about 1cm long by 1cm wide.	Figure 3 Figure 4
R-H-1.0-11.5-B	4cm long stain, 1cm wide that is about 1/3 the way down from the top.	Figure 5
F-S-1.0-11.5-A	Two stains right next to each other that each are about 2cm x .5cm that are both about half the way down the tube.	
F-H-1.0-11.5-B	A stain that is 2cm x .5cm that is near the top.	Figure 6
F-S-1.0-13-A	Two different lines of blotches that are about 2cm x .5cm that is located near the top.	Figure 7

Figures



Figure 1: Typical horizontal crack 0.25 cm below surface



Figure 2: Specimen F-S-.6-11.5-A



Figure 3: Specimen R-S-1.0-11.5-C – First Stain



Figure 4: Specimen R-S-1.0-11.5-C – Second Stain

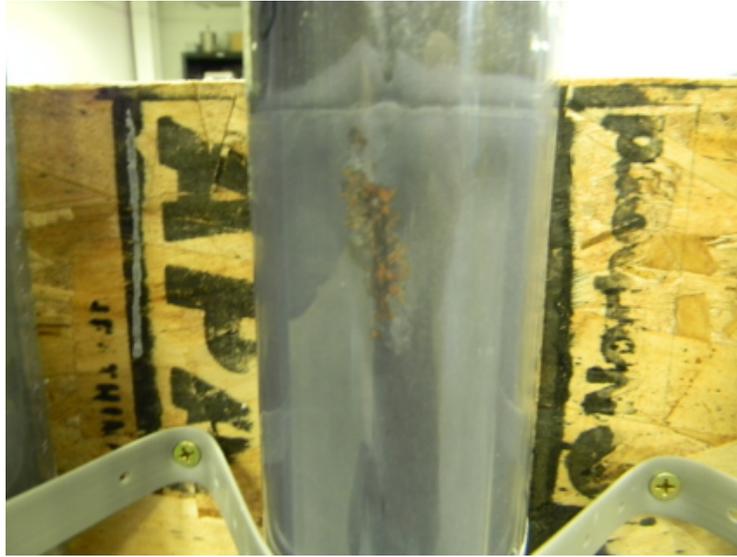


Figure 5: Specimen R-H-1.0-11.5-B



Figure 6: Specimen F-H-1.0-11.5-B



Figure 7: Specimen F-S-1.0-13-A

7.3 - February 2012 Inspection Report

Title: Interim Report on Long Term Corrosion Testing at UMD

Date: February 26, 2012

Prepared by: Eric Musselman

Included in this report is a summary of the inspection of the long term corrosion specimens that was conducted on February 24, 2012. The inspection was completed by 2 graduate students at UMD: Ben Thiesse and Waylon Munch.

The results of the inspection are summarized in Tables 1 and 2 on the next page.

Minimal cracking was observed in the specimens, with the only crack occurring near the free surface of some of the voided specimens. This is most likely indicative of shrinkage occurring on the top surface of the specimen. Corrosion was observed in 6 different specimens, all with chloride levels of 0.6% or higher. The majority of the corrosion seems to be occurring where the strand was in contact with the plastic tube, and there is a void in the grout. However, in at least one of the specimens (R-S-1.0-11.5-C which is a repaired, sealed, 1.0% chloride with 11.5 pints/bag of water) the corrosion being observed seems to indicate corrosion occurring in a well grouted region (particularly around the repair). In addition to the tables summarizing the results, figures are included that show the typical cracking observed as well as the corrosion for the specimens in which it was observed.

Key to specimen labels:

V= Voided

S = Solid

R = Repaired

H = Hole

S= Sealed

.04, .2, .4, .6, 1 = Chloride Level

11.5, 13, 14 = Water content (pints/bag)

A,B,C = Specimen indicator

Table 1: Summary of Cracking Observed

Specimen	Location	Size	Changed/Unchanged /New
V-H-.04-14-A	From top at 45% angle	2 cm	Unchanged
V-H-.2-11.5-B	Horizontal approx 0.25 cm from top	6 cm	Unchanged
V-H-.2-11.5-C	Horizontal approx 0.25 cm from top	5.5 cm	Unchanged
V-S-.4-11.5-A	Horizontal approx 0.25 cm from top	8 cm	Unchanged
V-S-.4-11.5-B	Horizontal approx 0.25 cm from top	8 cm	Unchanged
V-H-.4-11.5-A	Horizontal approx 0.25 cm from top	6 cm	Unchanged
V-H-.4-11.5-B	Horizontal approx 0.25 cm from top	8 cm	Unchanged
V-H-.4-11.5-C	Horizontal approx 0.25 cm from top	7 cm	Unchanged
R-S-1.0-11.5-C	Cracking below 3 blotch stains	3 cm	New
R-H-1.0-11.5-A	Cracks Surrounding Stain	1 cm	New

Table 2: Summary of Corrosion Observed

Specimen	Description	Figure Number	Changed/Unchanged /New
F-S-.6-11.5-A	Two 1 cm long stains about 1/3 the way down from top	Figure 2	Unchanged
R-S-1.0-11.5-C	Two stains. The first stain is a 3.5 cm long stain by 1/2 cm wide about a third of the way up from the bottom. The second stain was a series of three small blotches that sat on the "Repair Line". Each blotch was about 1cm long by 1cm wide.	Figure 3 Figure 4	Changed
R-H-1.0-11.5-A	1/2 cm circle stain, 2cm below the repair line	Figure 5	New
R-H-1.0-11.5-B	4cm long stain, 1cm wide that is about 1/3 the way down from the top.	Figure 6	Unchanged
F-S-1.0-11.5-A	Two stains right next to each other that each are about 2cm x .5cm that are both about half the way down the tube.	Figure 7	Unchanged
F-H-1.0-11.5-B	A stain that is 2cm x .5cm that is near the top. New stain 1cm x 1cm at very top on the 0° line	Figure 8	Unchanged/New
F-S-1.0-13-A	Two different lines of blotches that are about 2cm x .5cm that is located near the top.	Figure 9	Unchanged
F-S-1.0-13-B	A stain that is 1cm x 1cm near the top with smaller blotches below.	Figure 10	New
F-H-1.0-14-B	A stain that is 2cm x 2cm at the top of the sample.	Figure 11	New
F-H-1.0-14-C	A stain that is 1/2 cm x 1/2 cm at the top of the sample.	Figure 12	New

Figures



Figure 1: Typical horizontal crack 0.25 cm below surface



Figure 2: Specimen F-S-.6-11.5-A



Figure 3: Specimen R-S-1.0-11.5-C – First Stain



Figure 4: Specimen R-S-1.0-11.5-C – Second stain with cracking below the stains



Figure 5: Specimen R-H-1.0-11.5-A, Stain and cracks surrounding stain



Figure 6: Specimen R-H-1.0-11.5-B

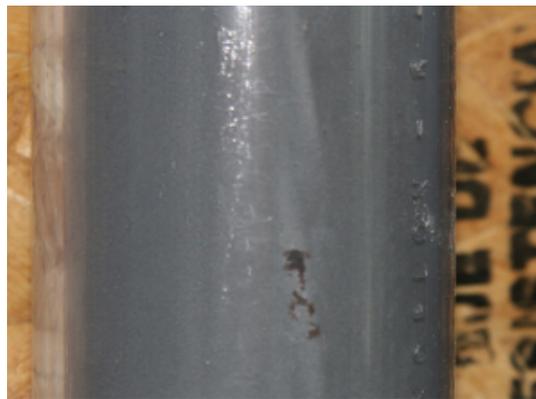


Figure 7: Specimen F-S-1.0-11.5-A



Figure 8: Specimen F-H-1.0-11.5-B

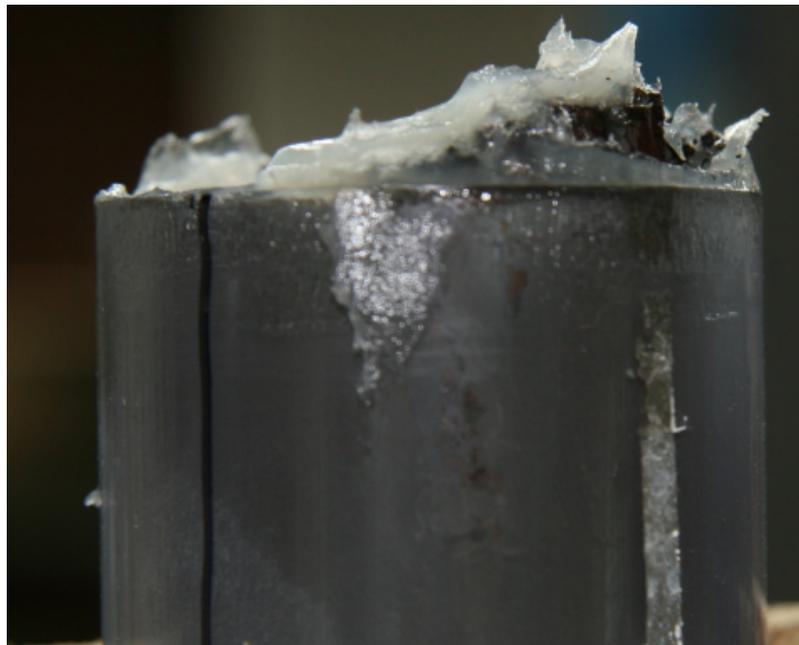


Figure 9: Specimen F-S-1.0-13-A



Figure 10: Specimen F-S-1.0-13-B



Figure 11: Specimen F-H-1.0-14-B

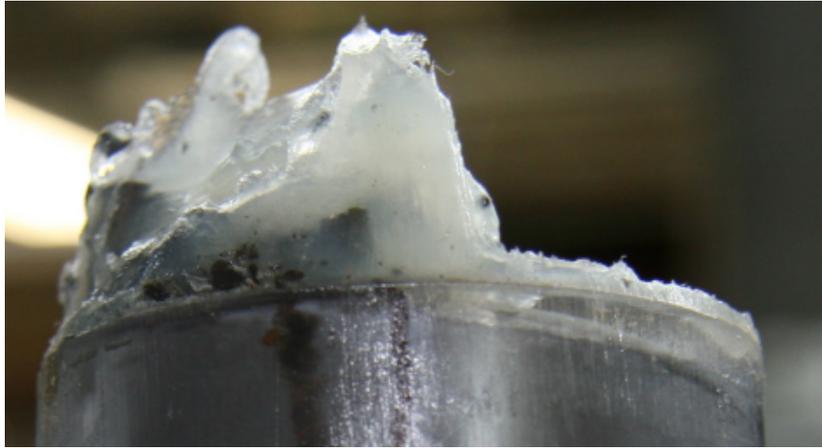


Figure 12: Specimen F-H-1.0-14-C

Newly Installed Sensors:



Sensor 1



Sensor 2



Sensor 3

7.4 - March 2012 Inspection Report

Title: Interim Report on Long Term Corrosion Testing at UMD

Date: March 28, 2012

Prepared by: Eric Musselman

Included in this report is a summary of the inspection of the long term corrosion specimens that was conducted on February 24, 2012. The inspection was completed by 2 graduate students at UMD: Ben Thiesse and Waylon Munch.

The results of the inspection are summarized in Tables 1 and 2 on the next page.

Minimal cracking was observed in the specimens, with the only crack occurring near the free surface of some of the voided specimens. This is most likely indicative of shrinkage occurring on the top surface of the specimen. Corrosion was observed in 6 different specimens, all with chloride levels of 0.6% or higher. The majority of the corrosion seems to be occurring where the strand was in contact with the plastic tube, and there is a void in the grout. However, in at least one of the specimens (R-S-1.0-11.5-C which is a repaired, sealed, 1.0% chloride with 11.5 pints/bag of water) the corrosion being observed seems to indicate corrosion occurring in a well grouted region (particularly around the repair). In addition to the tables summarizing the results, figures are included that show the typical cracking observed as well as the corrosion for the specimens in which it was observed.

Key to specimen labels:

V=Voided

S = Solid

R = Repaired

H = Hole

S= Sealed

.04, .2, .4, .6, 1 = Chloride Level

11.5, 13, 14 = Water content (pints/bag)

A,B,C = Specimen indicator

Table 1: Summary of Cracking Observed

Specimen	Location	Size	Changed/Unchanged /New
V-H-.04-14-A	From top at 45% angle	2 cm	Unchanged
V-H-.2-11.5-B	Horizontal approx 0.25 cm from top	6 cm	Unchanged
V-H-.2-11.5-C	Horizontal approx 0.25 cm from top	5.5 cm	Unchanged
V-S-.4-11.5-A	Horizontal approx 0.25 cm from top	8 cm	Unchanged
V-S-.4-11.5-B	Horizontal approx 0.25 cm from top	8 cm	Unchanged
V-H-.4-11.5-A	Horizontal approx 0.25 cm from top	6 cm	Unchanged
V-H-.4-11.5-B	Horizontal approx 0.25 cm from top	8 cm	Unchanged
V-H-.4-11.5-C	Horizontal approx 0.25 cm from top	7 cm	Unchanged
R-S-1.0-11.5-C	Cracking below 3 blotch stains	3 cm	Unchanged
R-H-1.0-11.5-A	Cracks Surrounding Stain	1 cm	Unchanged
R-H-1.0-11.5-B	Small Cracks below Stain	1 cm	New
F-S-1.0-11.5-C	Cracks running from top to stain	2 cm	New

Table 2: Summary of Corrosion Observed

Specimen	Description	Figure Number	Changed/Unchanged /New
F-S-.6-11.5-A	Two 1 cm long stains about 1/3 the way down from top	Figure 2	Unchanged & Shipped
R-S-1.0-11.5-C	Two stains. The first stain is a 4.5 cm long stain by 1 cm wide about a third of the way up from the bottom. The second stain was a series of three small blotches that sat on the "Repair Line". Each blotch was about 1cm long by 1cm wide.	Figure 3 Figure 4	Changed
R-H-1.0-11.5-A	½ cm circle stain, 2cm below the repair line	Figure 5	Unchanged
R-H-1.0-11.5-B	4cm long stain, 1cm wide that is about 1/3 the way down from the top.	Figure 6	Unchanged
F-S-1.0-11.5-A	Two stains right next to each other that each are about 2cm x .5cm that are both about half the way down the tube.	Figure 7	Unchanged & Shipped
F-H-1.0-11.5-B	A stain that is 2cm x .5cm that is near the top. New stain 1cm x 1cm at very top on the 0° line	Figure 8	Unchanged
F-S-1.0-13-A	Two different lines of blotches that are about 2cm x .5cm that is located near the top.	Figure 9	Unchanged
F-S-1.0-13-B	A stain that is 1cm x 1cm near the top with smaller	Figure 10	Unchanged

	blotches below.		
F-H-1.0-14-B	A stain that is 2cm x 2cm at the top of the sample.	Figure 11	Unchanged
F-H-1.0-14-C	A stain that is ½ cm x 2 ½ cm at the top of the sample.	Figure 12	Changed
F-S-.6-13-B	Three stains. The first is 5cm x 5cm mid way down surrounding the electrode pad. The second stain is 1cm x ½ cm, 3cm from the top. The third stain is ½ cm x 4cm, ½ way to the top near 360° line.	Figure 13 Figure 14 Figure 15	New/Changed
F-S-1.0-11.5-C	"Dot like" stains from top to 2cm down	Figure 16	New
F-S-1.0-14-C	2cm x ½ cm near top	Figure 17	New
F-S-.4-11.5-C	Three stains. First, ½ cm x ½ cm stain, 2 cm from top. Second, ½ cm x ½ cm stain, 4 cm from top. Third, ¼ cm x ½ cm, 2 cm down from top.	Figure 18	New
F-S-.4-13-C	½ cm x ½ cm, 2 cm down from top	Figure 19	New
F-S-.4-14-C	½ cm x ½ cm, 2 cm down from top	Figure 20	New

- Specimens F-S-.6-13-C, F-S-.6-14-C, F-S-1.0-13-C, F-S-1.0-11.5-C, F-S-1.0-14-C, V-S-.4-11.5-C, F-S-.4-11.5-C, F-S-.4-13-C, V-S-.4-14-C, F-S-.4-14-C, V-S-.63-11.5-C, and F-S-.6-11.5-C all have a roughly 5cm x 3cm corrosion stain around the electrode pad similar to Figure 21.

•
Figures



Figure 1: Typical horizontal crack 0.25 cm below surface



Figure 2: Specimen F-S-.6-11.5-A



Figure 3: Specimen R-S-1.0-11.5-C – First Stains



Figure 4: Specimen R-S-1.0-11.5-C – Second stain with cracking below the stains



Figure 5: Specimen R-H-1.0-11.5-A, Stain and cracks surrounding stain



Figure 6: Specimen R-H-1.0-11.5



Figure 7: Specimen F-S-1.0-11.5-A



Figure 8: Specimen F-H-1.0-11.5-B

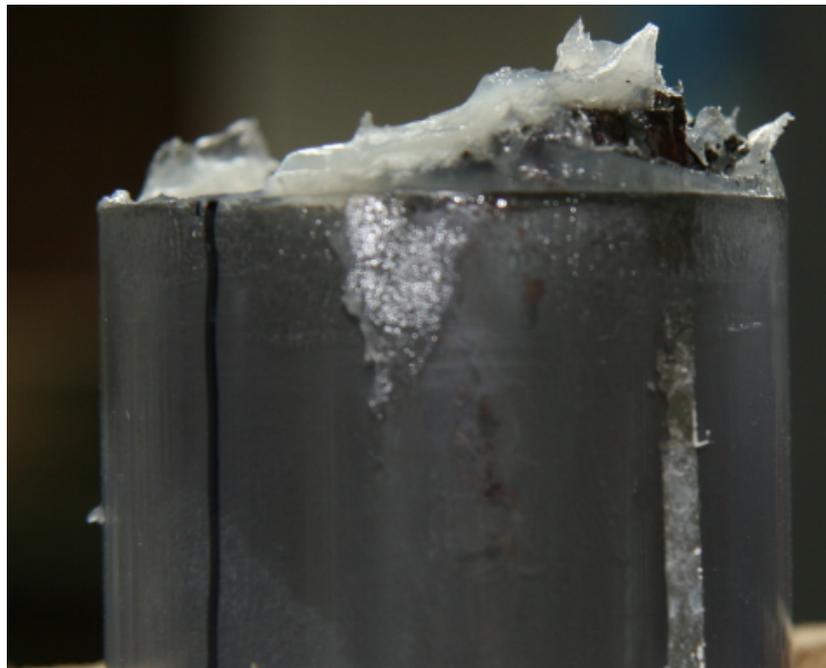


Figure 9: Specimen F-S-1.0-13-A



Figure 10: Specimen F-S-1.0-13-B



Figure 11: Specimen F-H-1.0-14-B

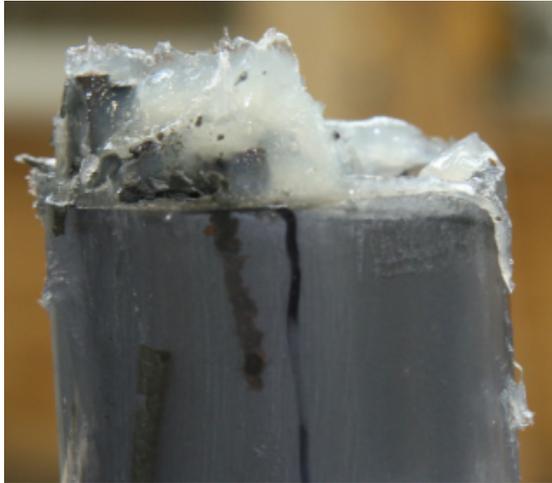


Figure 12: Specimen F-H-1.0-14-C



Figure 13: Specimen F-S-.6-13-B



Figure 14: Specimen F-S-.6-13-B



Figure 15: Specimen F-S-.6-13-B



Figure 16: F-S-1.0-11.5-C



Figure 17: F-S-1.0-14-C



Figure 18: F-S-.4-11.5-C



Figure 19: F-S-.4-13-C



Figure 20: F-S-.4-14-C



Figure 21: Corroded Electrode Pad

7.5 - April 2012 Inspection Report

Title: Interim Report on Long Term Corrosion Testing at UMD

Date: April 27, 2012

Prepared by: Eric Musselman

Included in this report is a summary of the inspection of the long term corrosion specimens that was conducted on April 27, 2012. The inspection was completed by 2 graduate students at UMD: Ben Thiesse and Waylon Munch.

The results of the inspection are summarized in Tables 1 and 2 on the next page.

Minimal cracking was observed in the specimens, with the only crack occurring near the free surface of some of the voided specimens. This is most likely indicative of shrinkage occurring on the top surface of the specimen. Corrosion was observed in 6 different specimens, all with chloride levels of 0.6% or higher. The majority of the corrosion seems to be occurring where the strand was in contact with the plastic tube, and there is a void in the grout. However, in at least one of the specimens (R-S-1.0-11.5-C which is a repaired, sealed, 1.0% chloride with 11.5 pints/bag of water) the corrosion being observed seems to indicate corrosion occurring in a well grouted region (particularly around the repair). In addition to the tables summarizing the results, figures are included that show the typical cracking observed as well as the corrosion for the specimens in which it was observed.

Key to specimen labels:

V= Voided

S = Solid

R = Repaired

H = Hole

S= Sealed

.04, .2, .4, .6, 1 = Chloride Level

11.5, 13, 14 = Water content (pints/bag)

A,B,C = Specimen indicator

Table 1: Summary of Cracking Observed

Specimen	Location	Size	Changed/Unchanged /New
V-H-.04-14-A	From top at 45% angle	2 cm	Unchanged
V-H-.2-11.5-B	Horizontal approx 0.25 cm from top	6 cm	Unchanged
V-H-.2-11.5-C	Horizontal approx 0.25 cm from top	5.5 cm	Unchanged
V-S-.4-11.5-A	Horizontal approx 0.25 cm from top	8 cm	Unchanged
V-S-.4-11.5-B	Horizontal approx 0.25 cm from top	8 cm	Unchanged
V-H-.4-11.5-A	Horizontal approx 0.25 cm from top	6 cm	Unchanged
V-H-.4-11.5-B	Horizontal approx 0.25 cm from top	8 cm	Unchanged
V-H-.4-11.5-C	Horizontal approx 0.25 cm from top	7 cm	Unchanged
R-S-1.0-11.5-C	Cracking below 3 blotch stains	3 cm	Unchanged
R-H-1.0-11.5-A	Cracks Surrounding Stain	1 cm	Unchanged
R-H-1.0-11.5-B	Small Cracks below Stain	1 cm	Unchanged
F-S-1.0-11.5-C	Cracks running from top to stain	2 cm	Unchanged
V-S-.75-11.5-B	Cracks running through stain	2 cm	New Specimen
F-H-.85-13-A	Cracks running through stain	8 cm	New Specimen
F-H-.85-13-B	Cracks running through stain	8 cm	New Specimen
F-H-1.0-13-B	Cracks running through stain	8 cm	New Specimen
F-H-1.0-13-C	Cracks running through stain	4cm	New Specimen
F-H-1.5-13-A	Cracks running through stain	Circumference of specimen	New Specimen
F-H-1.5-13-B	Cracks running through stain	8 cm	New Specimen

Table 2: Summary of Corrosion Observed

Specimen	Description	Figure Number	Changed/Unchanged /New/New Specimen	Rack Letter
R-S-1.0-11.5-C	Two stains. The first stain is a 4.5 cm long stain by 1 cm wide about a third of the way up from the bottom. The second stain was a series of three small blotches that sat on the "Repair Line". Each blotch was about 1cm long by 1cm wide.	Figure 2 Figure 3	Unchanged	L
R-H-1.0-11.5-A	½ cm circle stain, 2cm below the repair line	Figure 4	Unchanged	M
R-H-1.0-11.5-B	4cm long stain, 1cm wide that is about 1/3 the way down from the top.	Figure 5	Unchanged	M

F-H-1.0-11.5-B	A stain that is 2cm x .5cm that is near the top. New stain 1cm x 1cm at very top on the 0° line	Figure 6	Unchanged	M
F-S-1.0-13-A	Two different lines of blotches that are about 2cm x .5cm that is located near the top.	Figure 7	Unchanged	M
F-S-1.0-13-B	A stain that is 1cm x 1cm near the top with smaller blotches below.	Figure 8	Unchanged	M
F-H-1.0-14-B	A stain that is 2cm x 2cm at the top of the sample.	Figure 9	Unchanged	N
F-H-1.0-14-C	A stain that is ½ cm x 2 ½ cm at the top of the sample.	Figure 10	Unchanged	N
F-S-.6-13-B	Three stains. The first is 5cm x 5cm mid way down surrounding the electrode pad. The second stain is 1cm x ½ cm, 3cm from the top. The third stain is ½ cm x 4cm, ½ way to the top near 360° line.	Figure 11 Figure 12 Figure 13	Unchanged	T
F-S-1.0-11.5-C	"Dot like" stains from top to 2cm down	Figure 14	Unchanged	T
F-S-1.0-14-C	2cm x ½ cm near top	Figure 15	Unchanged	T
F-S-.4-11.5-C	Three stains. First, ½ cm x ½ cm stain, 2 cm from top. Second, ½ cm x ½ cm stain, 4 cm from top. Third, ¼ cm x ½ cm, 2 cm down from top.	Figure 16	Unchanged	T
F-S-.4-13-C	½ cm x ½ cm, 2 cm down from top	Figure 17	Unchanged	T
F-S-.4-14-C	½ cm x ½ cm, 2 cm down from top	Figure 18	Unchanged	T
F-S-.75-11.5-A	1cm x ½ cm, 2cm from top	Figure 19	New Specimen	A
F-S-.75-11.5B	1cm x 1cm, 3cm from top	Figure 20	New Specimen	A
V-S-.75-11.5-A	2cm x ½ cm, half way down	Figure 21	New Specimen	A
V-S-.75-11.5-B	Spots 2cm down, cracks running through	Figure 22	New Specimen	A
V-S-.75-11.5-C	2cm x ½ cm, 1 cm down from top	Figure 23	New Specimen	A
F-S-.85-13-A	Two Stains; First is 1 ½ cm x ½ cm, second is 2 ½ cm x 1 cm. Both 1 ½ cm from top	Figure 24	New Specimen	B
F-S-.4-11.5-B	1cm x ½ cm, 2cm from top	Figure 25	New Specimen	
F-S-.4-11.5-C	½ cm circle, 1 cm from top	Figure 26	New Specimen	B
F-H-.4-13-C	½ cm x 1cm, 1 ½ cm down from top	Figure 27	New Specimen	C
V-S-.65-11.5-C	1cm x ½ cm, 4cm down from top	Figure 28	New Specimen	C
F-H-.75-13-A	½ cm circle, 1 cm from top	Figure 29	New Specimen	D
F-H-.75-13-B	½ cm circle, 1 cm from top	Figure 30	New Specimen	D
F-H-.75-13-C	1cm x ½ cm, 3 cm from top	Figure 31	New Specimen	D
V-S-.4-13-B	1 ½ cm x ½ cm, 4 cm from top	Figure 32	New Specimen	D
F-S-.65-11.5-A	¼ cm x ¼ cm, ½ cm from top	Figure 33	New Specimen	E
F-S-.65-11.5-B	2 ½ cm x 1 cm, 3 cm from top	Figure 34	New Specimen	E
V-S-1.0-11.5-A	2 ½ cm x 1 cm, 3 cm from top	Figure 35	New Specimen	F

V-S-1.0-11.5-B	1 ½ cm x ½ cm, ½ cm from top	Figure 36	New Specimen	F
F-S-.4-13-F	¼ cm x ¼ cm, 2 ½ cm from top	Figure 37	New Specimen	H
F-H-.65-13-A	1 ½ cm x ½ cm, 1 ½ cm from top	Figure 38	New Specimen	H
F-H-.65-13-B	½ cm x ½ cm, 2 cm from top	Figure 39	New Specimen	H
V-S-.85-13-B	Three Stains: 1) 1cm x ½ cm 2) 1 ½ cm x 1 cm 3) ¼ cm dots	Figure 40 Figure 41 Figure 42	New Specimen	J
V-S-.85-13-C	2cm x 1cm, 1cm from top	Figure 43	New Specimen	J
F-S-1.0-11.5-B	Two Stains: 1) ½ cm x ½ cm 2) 1 ¼ cm x ½ cm	Figure 44	New Specimen	K
V-S-1.0-11.5-A	Two Stains: 1) 1cm x ½ cm, 2 cm from top 2) 2 ¼ cm x 1 cm, 4 cm from top	Figure 45	New Specimen	L
F-S-1.0-11.5-C	1 cm x ½ cm, 2 cm from top	Figure 46	New Specimen	L
F-S-1.0-14-B	1 ½ cm x ½ cm on top	Figure 47	New	N
F-S-.65-13-B	2cm x 1 cm, 1 ½ cm from top	Figure 48	New Specimen	N
F-S-.65-13-C	2cm x ½ cm, 2cm from top	Figure 49	New Specimen	N
F-S-.75-13-B	1 ½ cm x ½ cm, 1 ½ cm from top	Figure 50	New Specimen	O
F-S-.75-13-C	½ cm x 1cm, 1cm from top	Figure 51	New Specimen	O
F-S-.85-11.5-B	1cm, ½ cm, ½ cm from top	Figure 52	New Specimen	O
F-H-.85-13-A	.2cm x ½ cm, 1cm from top – Crack through stain	Figure 53	New Specimen	O
F-H-.85-13-B	2 Spots, each ½ cm x ½ cm - Crack through stain	Figure 54	New Specimen	O
F-H-1.0-13-B	Spot below crack - .2cm x ½ cm	Figure 55	New Specimen	O
F-H-.85-13-C	½ cm x ½ cm, 1 ½ cm from top	Figure 56	New Specimen	O
F-H-1.0-13-C	2 spots, each ½ cm x ½ cm	Figure 57	New Specimen	O
V-S-.75-13-C	1 ½ cm x ½ cm, ½ cm from top	Figure 58	New Specimen	O
F-H-1.5-13-A	.3cm x ½ cm, 3 cm from top	Figure 59	New Specimen	P
F-H-1.5-13-B	1cm x 1cm, 3cm from top	Figure 60	New Specimen	P
V-S-1.0-13-C	1 ½ cm x 1cm, ½ cm from top	Figure 61	New Specimen	P
F-H-1.5-13-C	2 Stains, both 1cm x 1cm	Figure 62	New Specimen	P
F-S-1.5-11.5-A	1cm x 1cm, 2cm from top	Figure 63	New Specimen	P
F-S-1.5-11.5-B	2 ½ cm x 1cm, 3cm from top	Figure 64	New Specimen	P
F-S-1.5-11.5-C	Two Stains: 1) 1cm x ½ cm, 2 cm from top 2) 2 cm x 1cm, 3 ½ cm from top	Figure 65	New Specimen	P
F-S-1.5-13-B	1 ½ cm x ½ cm, 2 ½ cm from top	Figure 66	New Specimen	P
V-S-1.5-13-C	2 ½ cm x 1cm, 3cm from top	Figure 67	New Specimen	P
F-S-1.0-13-A	Two Stains: 1) 2cm x ½ cm, 3cm from top 2) 1cm x 1cm, 3cm from top	Figure 69	New Specimen	P

- Specimens F-S-.6-13-C, F-S-.6-14-C, F-S-1.0-13-C, F-S-1.0-11.5-C, F-S-1.0-14-C, V-S-.4-11.5-C, F-S-.4-11.5-C, F-S-.4-13-C, V-S-.4-14-C, F-S-.4-14-C, V-S-.63-11.5-C, and F-S-.6-11.5-C all have a roughly 5cm x 3cm corrosion stain around the electrode pad similar to Figure 70.

Figures



Figure 1: Typical horizontal crack 0.25 cm below surface



Figure 2: Specimen R-S-1.0-11.5-C – First Stain



Figure 3: Specimen R-S-1.0-11.5-C – Second stain with cracking below the stains



Figure 4: Specimen R-H-1.0-11.5-A, Stain and cracks surrounding stain



Figure 5: Specimen R-H-1.0-11.5-B



Figure 6: Specimen F-H-1.0-11.5-B

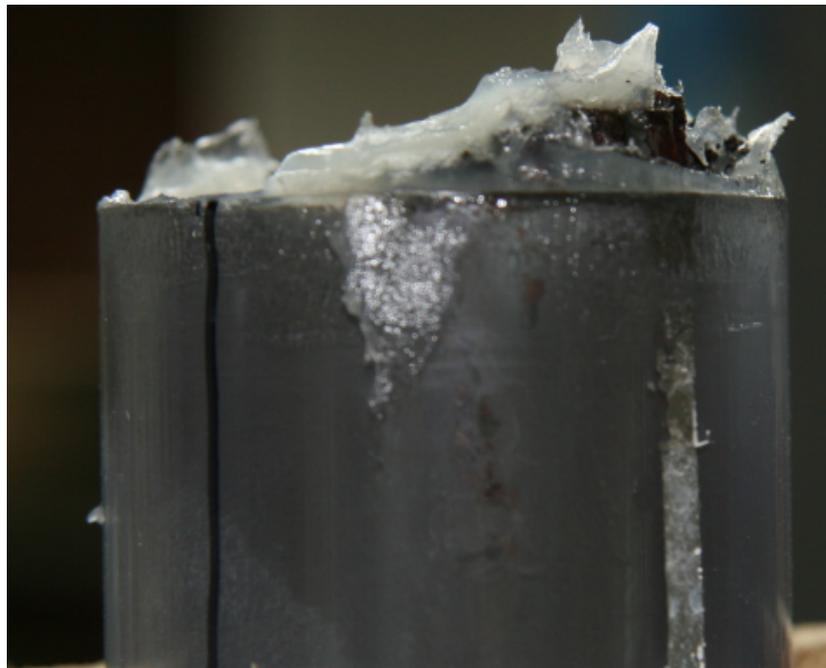


Figure 7: Specimen F-S-1.0-13-A



Figure 8: Specimen F-S-1.0-13-B



Figure 9: Specimen F-H-1.0-14-B

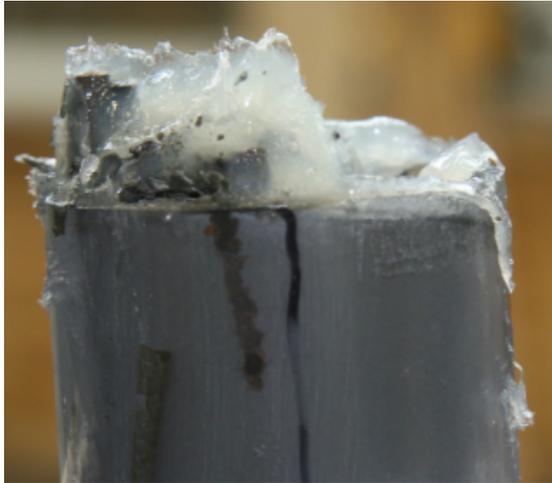


Figure 10: Specimen F-H-1.0-14-C



Figure 11: Specimen F-S-.6-13-B



Figure 12: Specimen F-S-.6-13-B



Figure 13: Specimen F-S-.6-13-B



Figure 14: F-S-1.0-11.5-C



Figure 15: F-S-1.0-14-C

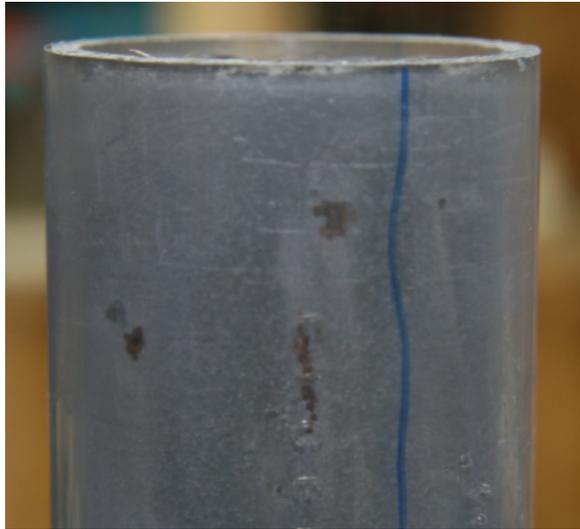


Figure 16: F-S-.4-11.5-C



Figure 17: F-S-.4-13-C



Figure 18: F-S-.4-14-C



Figure 19: F-S-.75-11.5-A



Figure 20: F-S-.75-11.5B



Figure 21: V-S-.75-11.5-A



Figure 22: V-S-.75-11.5-B



Figure 23: V-S-.75-11.5-C



Figure 24: F-S-.85-13-A

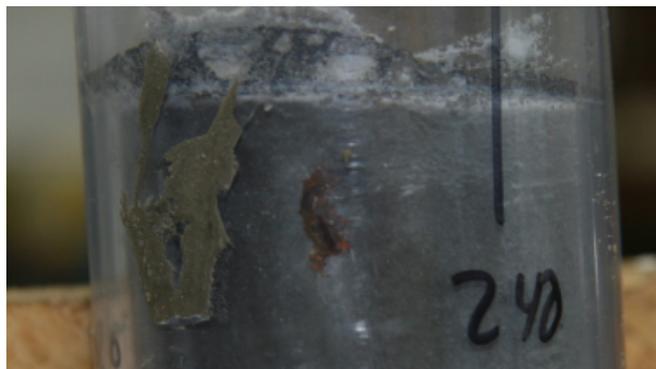


Figure 25: F-S-.4-11.5-B



Figure 26: F-S-.4-11.5-C



Figure 27: F-H-.4-13-C



Figure 28: V-S-.65-11.5-C



Figure 29: F-H-.75-13-A



Figure 30: F-H-.75-13-B



Figure 31: F-H-.75-13-C



Figure 32: V-S-.4-13-B

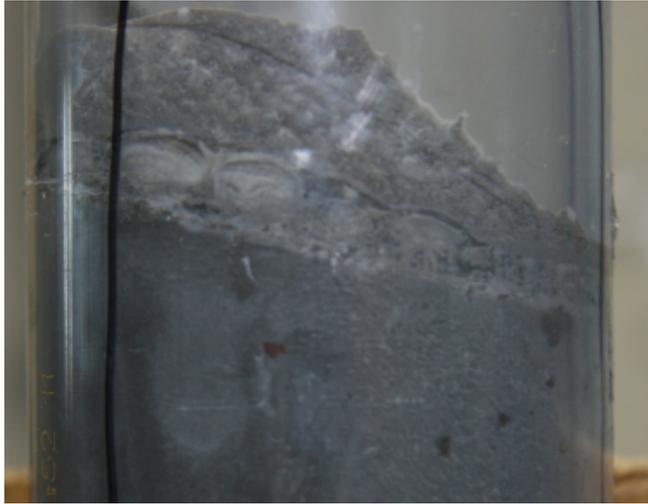


Figure 33: F-S-.65-11.5-A



Figure 34: F-S-.65-11.5-B



Figure 35: V-S-1.0-11.5-A



Figure 36: V-S-1.0-11.5-B

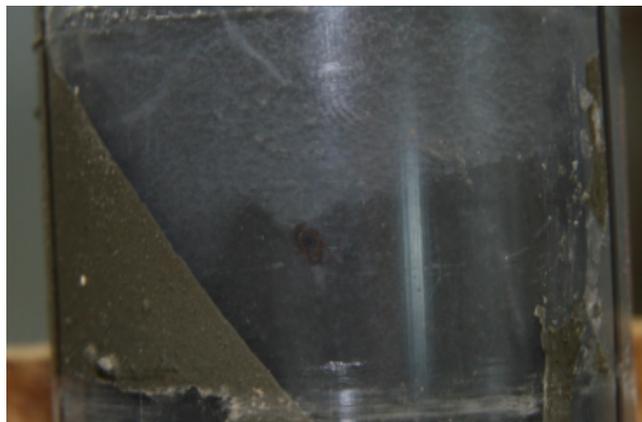


Figure 37: F-S-.4-13-F



Figure 38: F-H-.65-13-A



Figure 39: F-H-.65-13-B



Figure 40: V-S-.85-13-B



Figure 41: V-S-.85-13-B



Figure 42: V-S-.85-13-B



Figure 43: V-S-.85-13-C



Figure 44: F-S-1.0-11.5-B



Figure 45: V-S-1.0-11.5-A



Figure 46: F-S-1.0-11.5-C



Figure 47: F-S-1.0-14-B



Figure 48: F-S-.65-13-B



Figure 49: F-S-.65-13-C



Figure 50: F-S-.75-13-B



Figure 51: F-S-.75-13-C



Figure 52: F-S-.85-11.5-B



Figure 53: F-H-.85-13-A



Figure 54: F-H-.85-13-B



Figure 55: F-H-1.0-13-B



Figure 56: F-H-.85-13-C



Figure 57: F-H-1.0-13-C



Figure 58: V-S-.75-13-C



Figure 59: F-H-1.5-13-A



Figure 60: F-H-1.5-13-B



Figure 61: V-S-1.0-13-C



Figure 62: F-H-1.5-13-C



Figure 63: F-S-1.5-11.5-A



Figure 64: F-S-1.5-11.5-B



Figure 65: F-S-1.5-11.5-C



Figure 66: F-S-1.5-13-B



Figure 67: V-S-1.5-13-C



Figure 69: F-S-1.0-13-A



Figure 70: Corroded Electrode Pad

7.6 - May 2012 Inspection Report

Title: Interim Report on Long Term Corrosion Testing at UMD

Date: May 29, 2012

Prepared by: Eric Musselman and Ben Thiesse

Included in this report is a summary of the inspection of the long term corrosion specimens that was conducted on May 29, 2012. The inspection was completed by 2 graduate students at UMD: Ben Thiesse and Waylon Munch.

The results of the inspection are summarized in Tables 1 and 2 on the next page. This interim report is the first to include the inspection of the second set of long term corrosion samples, which were cast on March 28th. As indicated below, many of these samples exhibit a small amount of corrosion towards the top of the specimen where the strand is in contact with the wall of the tube. This occurs for all chloride levels cast in the second set. The majority of the older samples remained unchanged, with only one sample showing new evidence of corrosion (a sample with 1.0% chlorides).

Key to specimen labels:

V= Voided

F = Fully grouted

R = Repaired

H = Hole

S= Sealed

.04, .2, .4, .6, 1 = Chloride Level

11.5, 13, 14 = Water content (pints/bag)

A,B,C = Specimen indicator

2 = Specimen cast in second batch of samples (cast on March 28th 2012)

Table 1: Summary of Cracking Observed

Specimen	Location	Length of Crack	Changed/Unchanged /New
V-H-.04-14-A	From top at 45% angle	2 cm	Unchanged
V-H-.2-11.5-B	Horizontal approx 0.25 cm from top	6 cm	Unchanged
V-H-.2-11.5-C	Horizontal approx 0.25 cm from top	5.5 cm	Unchanged
V-S-.4-11.5-A	Horizontal approx 0.25 cm from top	8 cm	Unchanged
V-S-.4-11.5-B	Horizontal approx 0.25 cm from top	8 cm	Unchanged
V-H-.4-11.5-A	Horizontal approx 0.25 cm from top	6 cm	Unchanged
V-H-.4-11.5-B	Horizontal approx 0.25 cm from top	8 cm	Unchanged
V-H-.4-11.5-C	Horizontal approx 0.25 cm from top	7 cm	Unchanged
R-S-1.0-11.5-C	Cracking below 3 blotch stains	3 cm	Unchanged
R-H-1.0-11.5-A	Cracks Surrounding Stain	1 cm	Unchanged
R-H-1.0-11.5-B	Small Cracks below Stain	1 cm	Unchanged
F-S-1.0-11.5-C-2	Cracks running from top to stain	2 cm	Unchanged
V-S-.75-11.5-B-2	Cracks running through stain	2 cm	Unchanged
F-H-.85-13-A-2	Cracks running through stain	8 cm	Unchanged
F-H-.85-13-B-2	Cracks running through stain	10 cm	Changed
F-H-1.0-13-B-2	Cracks running through stain	8 cm	Unchanged
F-H-1.0-13-C-2	Cracks running through stain	4cm	Unchanged
F-H-1.5-13-A-2	Cracks running through stain	Circumference of specimen	Unchanged
F-H-1.5-13-B-2	Cracks running through stain	8 cm	Unchanged
F-H-1.5-13-C-2	Cracks running through stain	5 cm	New
F-S-1.5-13-C-2	Crack running through stain	4 cm	New
V-S-1.5-11.5-A-	Vertical crack	4 cm	New

2			
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The number two in the specimen name represents that it was made in the second batch of specimens and has a grey cap instead of a white cap.

Table 2: Summary of Corrosion Observed

Specimen	Description	Figure Number	Changed/Unchanged /New	Rack Letter
R-S-1.0-11.5-C	Two stains. The first stain is a 4.5 cm long stain by 1 cm wide about a third of the way up from the bottom. The second stain was a series of three small blotches that sat on the "Repair Line". Each blotch was about 1cm long by 1cm wide.	Figure 2 Figure 3	Unchanged	L
R-H-1.0-11.5-A	½ cm circle stain, 2cm below the repair line	Figure 4	Unchanged	M
R-H-1.0-11.5-B	4cm long stain, 1cm wide that is about 1/3 the way down from the top.	Figure 5	Unchanged	M
F-H-1.0-11.5-B	A stain that is 2cm x .5cm that is near the top. New stain 1cm x 1cm at very top on the 0° line	Figure 6	Unchanged	M
F-S-1.0-13-A	Two different lines of blotches that are about 2cm x .5cm that is located near the top.	Figure 7	Unchanged	M
F-S-1.0-13-B	A stain that is 1cm x 1cm near the top with smaller blotches below.	Figure 8	Unchanged	M
F-H-1.0-14-B	A stain that is 2cm x 2cm at the top of the sample.	Figure 9	Unchanged	N
F-H-1.0-14-C	A stain that is ½ cm x 2 ½ cm at the top of the sample.	Figure 10	Unchanged	N
F-S-.6-13-B	Three stains. The first is 5cm x 5cm mid way down surrounding the electrode pad. The second stain is 1cm x ½ cm, 3cm from the top. The third stain is ½ cm x 4cm, ½ way to the top near 360° line.	Figure 11 Figure 12 Figure 13	Unchanged	T
F-S-1.0-11.5-C	"Dot like" stains from top to 2cm down	Figure 14	Unchanged	T
F-S-1.0-14-C	2cm x ½ cm near top	Figure 15	Unchanged	T
F-S-.4-11.5-C	Three stains. First, ½ cm x ½ cm stain, 2 cm from top. Second, ½ cm x ½ cm stain, 4 cm from top. Third, ¼ cm x ½ cm, 2 cm down from top.	Figure 16	Unchanged	T

F-S-.4-13-C	½ cm x ½ cm, 2 cm down from top	Figure 17	Unchanged	T
F-S-.4-14-C	½ cm x ½ cm, 2 cm down from top	Figure 18	Unchanged	T
F-S-.75-11.5-A-2	1cm x 1cm, 2cm from top	Figure 19	Changed	A
F-S-.75-11.5B-2	2.5cm x 1cm, 3cm from top	Figure 20	Changed	A
V-S-.75-11.5-A-2	Two Stains: First is unchanged, 2cm x ½ cm, half way down, Second is new 2cm x ¼ cm, 2cm below other stain.	Figure 21	Changed	A
V-S-.75-11.5-B-2	Spots 2cm down, cracks running through	Figure 22	Unchanged	A
V-S-.75-11.5-C-2	2cm x ½ cm, 1 cm down from top	Figure 23	Unchanged	A
F-S-.85-13-A-2	Three Stains; First Two are unchanged: First is 1 ½ cm x ½ cm, second is 2 ½ cm x 1 cm. Both 1 ½ cm from top. Third stain is new, ¼ cm x 1 cm, 2cm right of first two stains.	Figure 24	Changed	B
F-S-.4-11.5-B-2	1cm x ½ cm, 2cm from top	Figure 25	Unchanged	
F-S-.4-11.5-C-2	½ cm circle, 1 cm from top	Figure 26	Unchanged	B
F-H-.4-13-C-2	½ cm x 1cm, 1 ½ cm down from top	Figure 27	Unchanged	C
V-S-.65-11.5-C-2	1cm x ½ cm, 4cm down from top	Figure 28	Unchanged	C
F-H-.75-13-A-2	½ cm circle, 1 cm from top	Figure 29	Unchanged	D
F-H-.75-13-B-2	½ cm circle, 1 cm from top	Figure 30	Unchanged	D
F-H-.75-13-C-2	1cm x ½ cm, 3 cm from top	Figure 31	Unchanged	D
V-S-.4-13-B-2	Unchanged: 1 ½ cm x ½ cm, 4 cm from top Changed: 1 cm below old stain, 2cm x ¼ cm	Figure 32	Changed	D
F-S-.65-11.5-A-2	¼ cm x ¼ cm, ½ cm from top	Figure 33	Unchanged	E
F-S-.65-11.5-B-2	2 ½ cm x 1 cm, 3 cm from top	Figure 34	Unchanged	E
V-S-1.0-11.5-A-2	2 ½ cm x 1 cm, 3 cm from top	Figure 35	Unchanged	F
V-S-1.0-11.5-B-2	1 ½ cm x ½ cm, ½ cm from top	Figure 36	Unchanged	F
F-S-.4-13-D-2	1 cm x 1/8 cm	Figure 37	New	H
F-S-.4-13-F-2	¼ cm x ¼ cm, 2 ½ cm from top	Figure 38	Unchanged	H
F-H-.65-13-A-2	2 cm x 1 cm, 1 ½ cm from top	Figure 39	Changed	H
F-H-.65-13-B-2	½ cm x ½ cm, 2 cm from top	Figure 40	Unchanged	H
V-S-.85-13-B-2	Three Stains: 1) 1cm x ½ cm (Unchanged) 2) 2 ½ cm x 1 cm (Changed) 3) ¼ cm dots (Unchanged)	Figure 41 Figure 42 Figure 43	Changed	J
V-S-.85-13-C-2	3cm x 1 ½ cm, 1cm from top	Figure 44	Changed	J
F-S-1.0-11.5-B-2	Three Stains: 1) 1 cm x 1cm (Changed) 2) 1 ¼ cm x ½ cm (Unchanged) 3) 1 ½ cm x 1 cm (New)	Figure 45	New, Changed	K
V-S-1.0-11.5-A-2	Two Stains: 1) 2cm x ¾ cm, 2 cm from top 2) 2 ½ cm x 1 cm, 4 cm from top	Figure 46	Changed	L
F-S-1.0-11.5-C-2	Two Stains: 1) 1 cm x ½ cm, 2 cm from top (Changed) 2) ½ cm x ½ cm (New) 2 cm to the right of first	Figure 47	Changed & New	L

F-S-1.0-14-B	1 ½ cm x ½ cm on top	Figure 48	Unchanged	N
F-S-.65-13-B-2	2cm x 1 cm, 1 ½ cm from top	Figure 49	Unchanged	N
F-S-.65-13-C-2	2cm x ½ cm, 2cm from top	Figure 50	Unchanged	N
F-S-.75-13-B-2	1) ½ cm x ½ cm, 1 ½ cm from top (Unchanged) 2) 1 cm x ¼ cm, 2cm right of first stain (New)	Figure 51	Unchanged & New	O
F-S-.75-13-C-2	1) 2cm x 1 ½ cm, 1cm from top 2) ½ cm x ½ cm, ½ cm from top	Figure 52	Changed & New	O
F-S-.85-11.5-B-2	2 cm x 1 cm, ½ cm from top	Figure 53	Changed	O
F-H-.85-13-A-2	1) .2cm x ½ cm, 1cm from top (Unchanged) 2) ½ cm x ½ cm, below first stain. Crack running through 1 st stain.	Figure 54	Unchanged & New	O
F-H-1.0-13-A-2	1 cm x ½ cm, 2 cm down from top.	Figure 55	New	O
F-H-.85-13-B-2	1) 2 Spots, each ½ cm x ½ cm - Crack through stain (Unchanged) 2) 1cm x 1 cm (New)	Figure 56	Unchanged & New	O
F-H-1.0-13-B-2	1) Spot below crack - .2cm x ½ cm (Unchanged) 2) 1 ½ cm x ½ cm, on 0° line (New)	Figure 57	Unchanged & New	O
F-H-.85-13-C-2	½ cm x ½ cm, 1 ½ cm from top	Figure 58	Unchanged	O
F-H-1.0-13-C-2	2 spots, each ½ cm x ½ cm	Figure 59	Unchanged	O
V-S-.75-13-C-2	1 ½ cm x ½ cm, ½ cm from top	Figure 60	Unchanged	O
F-H-1.5-13-A-2	1) .3cm x ½ cm, 3 cm from top (Unchanged) 2) ¼ cm x ¼ cm, 2cm right of first stain (New)	Figure 61	Unchanged & New	P
F-H-1.5-13-B-2	1) 1cm x 1cm, 3cm from top (Unchanged) 2) ½ cm x ½ cm, 1 cm right of first stain (New) 3) Specks below first stain (New)	Figure 62	Unchanged & New	P
V-S-1.0-13-C-2	1 ½ cm x 1cm, ½ cm from top	Figure 63	Unchanged	P
F-H-1.5-13-C-2	1) 2cm x 1cm, 3 cm from top 2) ½ cm x 2 cm, 3 cm from top	Figure 64	Changed	P
F-S-1.5-11.5-A-2	2cm x 2cm, 2cm from top	Figure 65	Unchanged	P
F-S-1.5-13-C-2	½ cm x 1 cm, 2 cm from top	Figure 66	New	P
F-S-1.5-11.5-B-2	1). 3cm x 1cm, 3cm from top (Changed) 2). ½ cm x ½ cm, 3 cm from top (New)	Figure 67	Changed & New	P
F-S-1.5-11.5-C-2	1) 1cm x ½ cm, 2 cm from top (Unchanged) 2) 2 ½ cm x 1cm, 3 ½ cm from top (Changed) 3) ½ cm x ½ cm, ½ cm below first stain (New) 4) five ½ cm x ½ cm splotches below first stain (New)	Figure 68	Unchanged, Changed & New	P
F-S-1.5-13-B-2	1 ½ cm x ½ cm, 2 ½ cm from top	Figure 69	Unchanged	P
V-S-1.5-13-C-2	2 ½ cm x 1 ½ cm, 3cm from top	Figure 70	Changed	P
F-S-1.0-13-A-2	1) 2 ½ cm x ½ cm, 3cm from top (Changed) 2) 1cm x 1cm, 3cm from top (Unchanged)	Figure 71	Changed	P
V-S-1.5-11.5-B-2	1cm x ½ cm, 3 cm from top	Figure 72	New	P

- Specimens F-S-.6-13-C, F-S-.6-14-C, F-S-1.0-13-C, F-S-1.0-11.5-C, F-S-1.0-14-C, V-S-.4-11.5-C, F-S-.4-11.5-C, F-S-.4-13-C, V-S-.4-14-C, F-S-.4-14-C, V-S-.63-11.5-C, and F-S-.6-11.5-C all have a roughly 5cm x 3cm stain around the electrode pad similar to Figure 73. This appears to be only a discoloration of the epoxy used to attach the electrode.

Figures



Figure 1: Typical horizontal crack 0.25 cm below surface



Figure 2: Specimen R-S-1.0-11.5-C – First Stain



Figure 3: Specimen R-S-1.0-11.5-C – Second stain with cracking below the stains



Figure 4: Specimen R-H-1.0-11.5-A, Stain and cracks surrounding stain



Figure 5: Specimen R-H-1.0-11.5-B



Figure 6: Specimen F-H-1.0-11.5-B

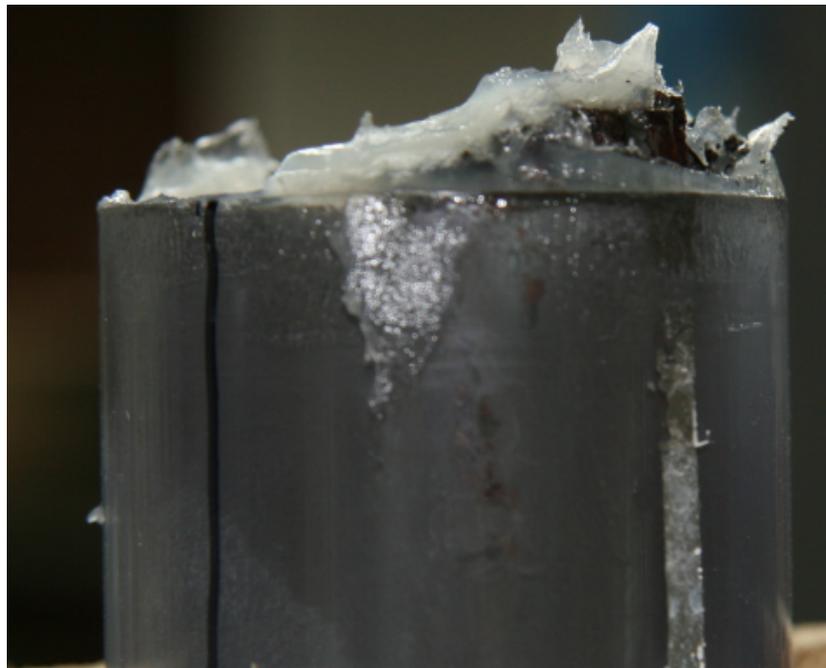


Figure 7: Specimen F-S-1.0-13-A



Figure 8: Specimen F-S-1.0-13-B



Figure 9: Specimen F-H-1.0-14-B

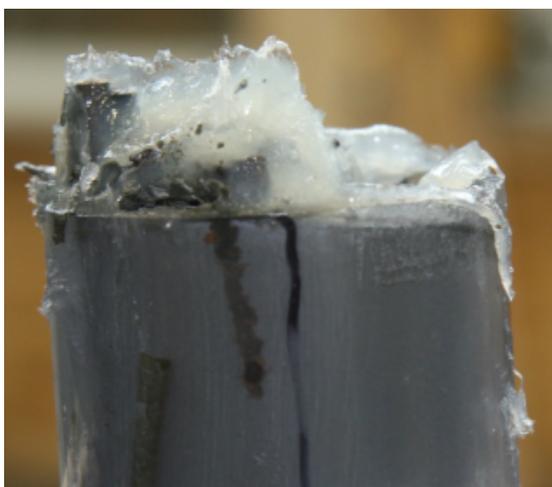


Figure 10: Specimen F-H-1.0-14-C



Figure 11: Specimen F-S-.6-13-B



Figure 12: Specimen F-S-.6-13-B



Figure 13: Specimen F-S-.6-13-B



Figure 14: F-S-1.0-11.5-C



Figure 15: F-S-1.0-14-C

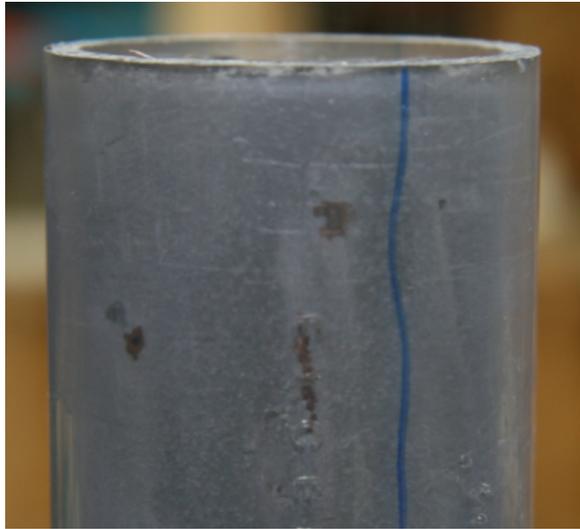


Figure 16: F-S-.4-11.5-C



Figure 17: F-S-.4-13-C



Figure 18: F-S-.4-14-C



Figure 19: F-S-.75-11.5-A-2



Figure 20: F-S-.75-11.5B-2



Figure 21: V-S-.75-11.5-A-2



Figure 22: V-S-.75-11.5-B-2



Figure 23: V-S-.75-11.5-C-2



Figure 24: F-S-.85-13-A-2



Figure 25: F-S-.4-11.5-B-2



Figure 26: F-S-.4-11.5-C-2



Figure 27: F-H-.4-13-C-2



Figure 28: V-S-.65-11.5-C-2



Figure 29: F-H-.75-13-A-2



Figure 30: F-H-.75-13-B-2

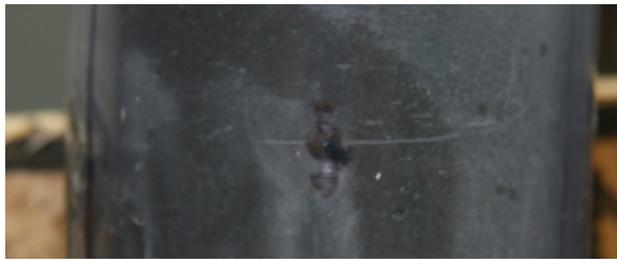


Figure 31: F-H-.75-13-C-2



Figure 32: V-S-.4-13-B-2



Figure 33: F-S-.65-11.5-A-2



Figure 34: F-S-.65-11.5-B-2



Figure 35: V-S-1.0-11.5-A-2



Figure 36: V-S-1.0-11.5-B-2



Figure 37: F-S-.4-13-D-2

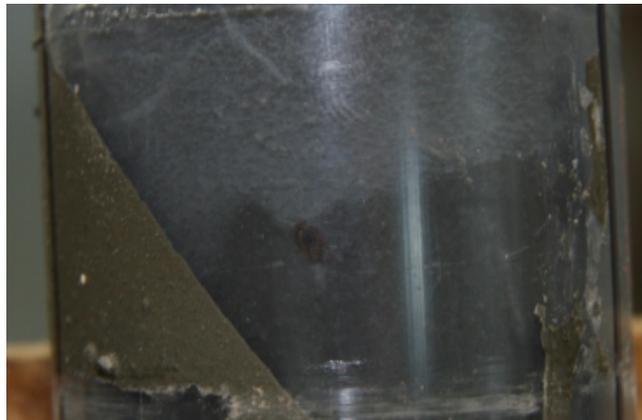


Figure 38: F-S-.4-13-F-2



Figure 39: F-H-.65-13-A-2



Figure 40: F-H-.65-13-B-2



Figure 41: V-S-.85-13-B-2



Figure 42: V-S-.85-13-B-2



Figure 43: V-S-.85-13-B-2



Figure 44: V-S-.85-13-C-2

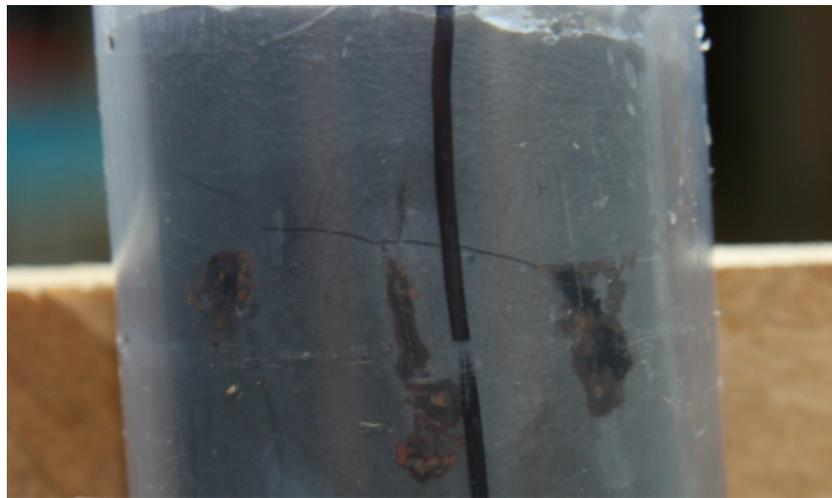


Figure 45: F-S-1.0-11.5-B-2



Figure 46: V-S-1.0-11.5-A-2



Figure 47: F-S-1.0-11.5-C-2



Figure 48: F-S-1.0-14-B



Figure 49: F-S-.65-13-B-2



Figure 50: F-S-.65-13-C-2



Figure 51: F-S-.75-13-B-2



Figure 52: F-S-.75-13-C-2



Figure 53: F-S-.85-11.5-B-2



Figure 54: F-H-.85-13-A-2

Figure 4.4.2: Specimen V-S-.85-13-B, Top portion of specimen

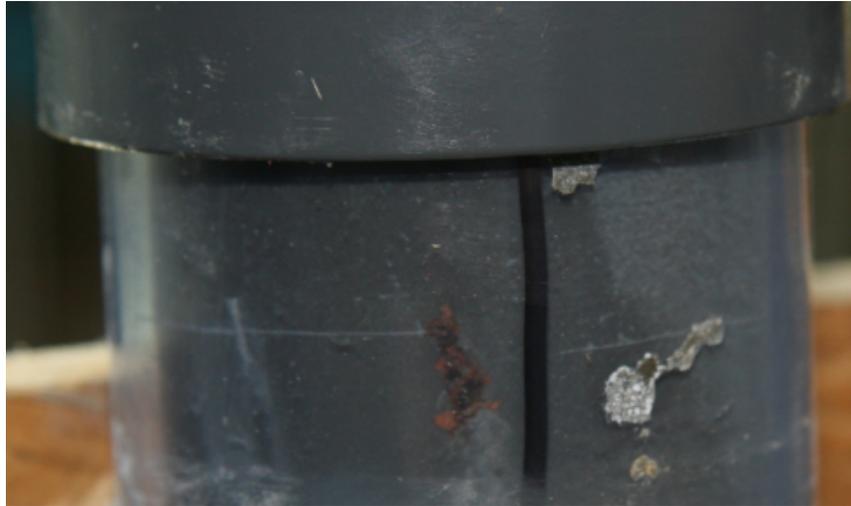


Figure 55: F-H-1.0-13-A-2



Figure 56: F-H-.85-13-B-2



Figure 57: F-H-1.0-13-B-2



Figure 58: F-H-.85-13-C-2



Figure 59: F-H-1.0-13-C-2



Figure 60: V-S-.75-13-C-2



Figure 61: F-H-1.5-13-A-2



Figure 62: F-H-1.5-13-B-2



Figure 63: V-S-1.0-13-C-2



Figure 64: F-H-1.5-13-C-2



Figure 65: F-S-1.5-11.5-A-2



Figure 66: F-S-1.5-13-C-2



Figure 67: F-S-1.5-11.5-B-2



Figure 68: F-S-1.5-11.5-C-2



Figure 69: F-S-1.5-13-B-2



Figure 70: V-S-1.5-13-C-2



Figure 71: F-S-1.0-13-A-2

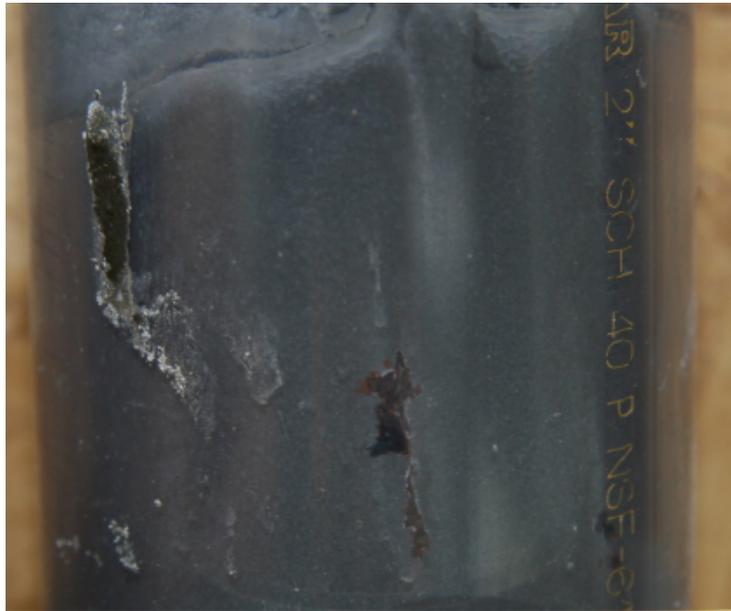


Figure 72: V-S-1.5-11.5-B-2



Figure 73: Staining on Electrode Pad