INVESTIGATION OF MMFX REINFORCING STEEL AND THE ADMIXTURE IPANEX FOR USE IN BRIDGE DECKS

By

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1. INTRODUCTION

1.1 Need for Durability in Bridges

A major concern for highway agencies across the country is the number of bridges that need major repair before the end of their design life. There are 592,116 bridges in the National Bridge Inventory (NBI) (FHWA 2004). 77,659 (13%) of these bridges are rated as structurally deficient. In Oklahoma there are 23,249 bridges of which 7,489 (32%) are rated structurally deficient. However, the Oklahoma Department of Transportation (ODOT) maintains only 6,743 bridges, of which 1,114 are rated as structurally deficient (Russell et al. 2004).

These bridges can be divided into three groups: Interstate, National Highway System (NHS) Non-Interstate, and State Transportation Project System (STP). A recent statistical analysis by Oklahoma State University revealed that over half of all structural deficiencies were caused by problems with the bridge deck. More specifically, problems in the bridge deck resulted in 67% of the structural deficiencies in Interstate bridges, 74% of the structural deficiencies in NHS Non-Interstate bridges, and 68% of the structural deficiencies in STP bridges. In reviewing the data, one concludes that the durability of Oklahoma bridge decks is a serious problem (Russell et al. 2004).

1.2 Addressing the Problem of Durability

The importance of designing and building durable bridge decks began to be emphasized in the early 1970's. A national policy was adopted in 1972 that required all federal aid projects to use some type of protective system for bridge decks (NCHRP 1979). In spite of this policy there are 9,603 bridges in the NBI that are rated as structurally deficient that were built from 1971 to 1995. The FHWA estimates that it would cost \$10.6 billion per year for 20 years to eliminate all deficiencies in every bridge in the United States (Engineering News Record 2002). In addition the cost to maintain the existing bridges over the same time period is estimated to be \$5.8 billion per year (Engineering News Record 2002).

Corrosion has been reported as the most common source of damage to bridges (Enright and Frangopol 2000). The approaches that have been devised in response to corrosion can be divided into two types. The first approach is to prevent or slow penetration of the chlorides that cause corrosion. This is accomplished by using quality concrete materials featuring a low water to cementitous ratio (w/cm), various admixtures, overlays, and membranes to help prevent or slow migration of chloride ions. The second approach is to utilize reinforcement that will not corrode or to inhibit the corrosion mechanism. This is commonly done by using epoxy coated reinforcement, but recently reinforcement made from stainless steel or high chromium steel have been considered.

1.3 Objectives of Research

The purpose of this research project is to investigate the ability of MMFX reinforcing and the IPANEX concrete admixture to diminish the effect of corrosion in bridge decks and increase overall bridge deck durability. In order to accomplish this, accelerated corrosion testing of specimens containing MMFX reinforcing, epoxy coated reinforcing, and uncoated or "black" reinforcement were conducted. Half of these specimens were constructed with IPANEX and half without IPANEX so that its effect could be observed with varying reinforcing steels and w/cm ratios.

The material properties of MMFX reinforcing and black steel were also evaluated to compare differences if any. These properties included yield strength, elastic modulus, and ultimate strength.

The ability of IPANEX to diminish corrosion was evaluated by testing the permeability of concrete containing IPANEX. The permeability of cores of bridge decks with and without IPANEX was measured. In addition, hardened properties of these cores were also measured to determine what effects, if any, IPANEX had on the hardened paste. Therefore, the objectives may be stated as:

1. Determine what effects, if any, IPANEX will have on bridge deck durability.
2. Make a recommendation to the ODOT regarding whether IPANEX should be used in future bridges.
3. Determine what effects, if any, MMFX will have on deck durability.
4. Make a recommendation to the ODOT regarding whether MMFX should be used in future bridges.

1.4 Scope

The testing program consisted of accelerated corrosion testing, tension tests of MMFX and uncoated Grade 60 steel, elastic modulus tests of IPANEX concrete, Rapid Chloride Ion Permeability Tests of cores, and compressive strength tests of cores.

These tests were conducted in order to:

1) Compare corrosion rates of epoxy coated and MMFX reinforcing steel;
2) Measure corrosion potential as a function of time;
3) Obtain material properties of MMFX and Grade 60 steel;
4) Determine chloride permeability of IPANEX concrete in comparison to non-IPANEX concrete;
5) Determine effects of IPANEX on the compressive strength; and,
6) Determine effects of IPANEX on elastic modulus of concrete.

2. BACKGROUND AND DEFINITIONS

2.1 Mechanics of Corrosion

In order for the steel to begin corroding four things are necessary: an anode, a cathode, oxygen and an electrolyte. The anode is defined as the location where the iron atom is oxidized which creates 2 electrons and a ferrous ion (Mindess et al. 2003):

$$Fe \rightarrow 2e^- + Fe^{2+}$$

The anode produces electrons that the cathode must consume. At the location of the cathode, water is reduced by oxygen to generate hydroxyl ions:

$$\frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2OH^-$$

Ferrous hydroxide is formed on the anode, which is converted into ferric hydroxide or rust:

$$Fe^{2+} + 2(OH)^- \rightarrow 2Fe(OH)_2$$

$$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3$$

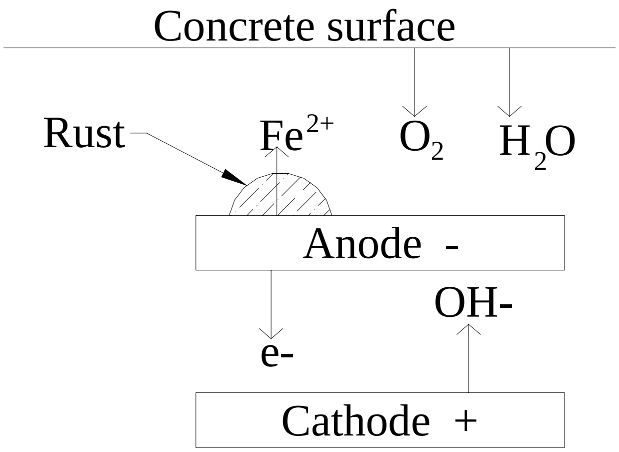


Figure 1: Corrosion of Steel in Concrete (Mindess et al. 2003)

Oxygen is needed to help oxidize the iron and produce the hydroxyl ions. Water is needed to sustain the reaction at the cathode. It also acts as the electrolyte by providing a medium that is capable of conducting the electrons.

Steel embedded in concrete will usually not corrode under normal conditions. This is due to the high alkalinity of the concrete; the pH is greater than 13. Due to high pH, the ferrous oxide ($Fe(OH)_2$) is oxidized to γ-ferric hydroxide at the anode:

$$Fe(OH)_2 + O_2 \rightarrow \gamma\text{-}FeOOH + H_2O$$

The γ-ferric hydroxide forms a film on the surface of the steel that restricts the access of moisture and oxygen to the steel. This prevents corrosion of the steel. However, this film can be destroyed by chloride ions in the concrete. A soluble iron-chloride complex forms which deposits ferrous oxide (rust) and then frees the chloride ion to carry on the damage.

$$Fe^{2+} + Cl^{-} \rightarrow [FeCl\ complex]^{+}$$

$$[FeCl]^{+} + 2OH^{-} \rightarrow Fe(OH)_2 + Cl^{-}$$

2.1.1 Microcell Corrosion

A micro cell forms when anodes and cathodes are present on the same piece of corroding material, for example a piece of reinforcing steel. Corrosion occurs in microcells at localized anodic areas on the reinforcing steel. In reinforced concrete (RC) the electrons are conducted by the reinforcing steel between anode and cathode. While micro cells probably exist in many RC structures, they are not the main cause of corrosion (Scannell and Clear 1990). The corrosion only occurs in local areas of the reinforcement, and the rate of corrosion is slow.

2.1.2 Macrocell Corrosion

When anodes and cathodes develop on different pieces of steel this is known as a macrocell. This type of corrosion can cause rapid deterioration, because entire layers of steel become anodic or cathodic. In bridge decks macro cells usually develop between the different mats of steel. The top mat becomes the anode and the bottom mat becomes the cathode.

In order for this to occur some type of electrical connection (moisture, chairs, ties, etc.) must be made between the mats. This type of corrosion is reported as the main cause of rapid deterioration of reinforcing steel (Scannell and Clear 1990).

2.1.2.1 Macrocell Current

An electrical circuit is created by the flow of electrons between the anode and cathode when a macrocell is formed. This flow of electrons is called the macro cell current. The macrocell current is a direct measure of the electrons released by the macro cell corrosion process so therefore it provides a direct measurement of macrocell corrosion activity (Scannell and Clear 1990).

The macro cell current is present in all macro cells, but because they are usually encased in concrete it is not feasible to measure them. In laboratory settings beams and slabs are cast with a top and bottom layer of reinforcing protruding. Electrical connections are made across the bars of the same level, and a resistor is placed between the layers of steel. The macro cell current can be back calculated by measuring the voltage across this resistor and rearranging Ohm’s Law to a form of:

$$I = \frac{V}{R}$$

Where I is the current in amps, V is the voltage in volts, and R is the resistance in ohms.

ASTM Test Method G 109 is a standard test performed in this same manner. Concrete beams are cast with one piece of reinforcing steel in the top and two pieces in the bottom. The top steel is the anode and the bottom steel is the cathode. A resistor is connected between the top and bottom steel. Voltage is measured across this resistor, and the macrocell current is calculated using Ohm's Law.

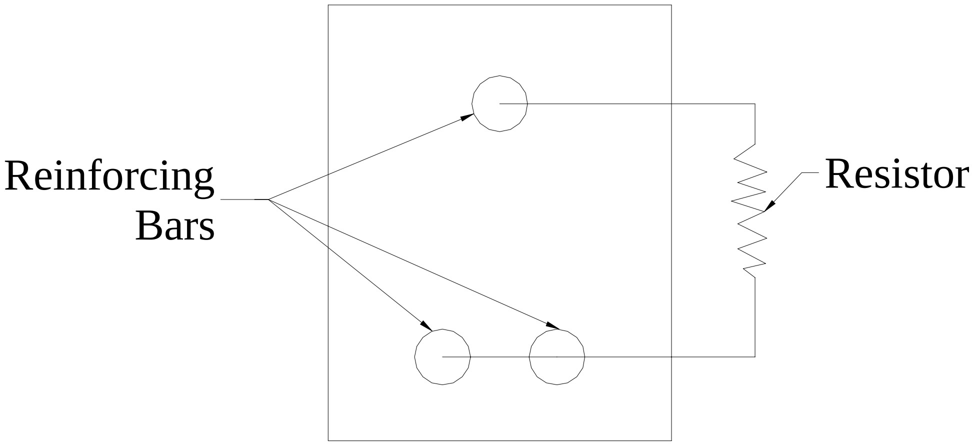


Figure 2: ASTM Test Method G 109

2.1.2.2 Corrosion Potential

A potential difference or voltage exists between each half of the macrocell. This is the electrical potential between anode and cathode. Because of seasonal changes and moisture variations, this voltage is not a reliable measure of corrosion in bridge decks. Therefore the potential or voltage is measured between the top layer of steel, or anode, and a standard reference electrode. The difference in voltage between the standard reference electrode and the anode is known as the corrosion potential.

This measurement is done by placing the positive lead of a voltmeter directly to the top layer of steel, and connecting the negative lead to the reference electrode. A path of moisture must also be present between the electrode and the concrete. Copper-copper sulfate cells and saturated Calomel cells are commonly used for reference electrodes.

The corrosion potential is not a measure of the rate of corrosion. It only measures the tendency of the reinforcement to corrode. Measurements of corrosion potential are commonly done on bridge decks where corrosion is suspected. The values of the potentials can be grouped into three main categories as shown in Table 2.1

Table 2.1 Interpretation of Corrosion Potentials (Clear 1974)

Corrosion Potential Value	**Interpretation**
350 mV CSE	High probability of corrosion
200 – 350 mV CSE	Uncertain
< 200 mV CSE	High probability of no corrosion

2.2 Literature Survey

A review of literature pertaining to bridge deck durability revealed five main causes of deterioration. These causes are:

1. Scaling;
2. Cracking;
3. Spalling;
4. Failure of deck joints, and;
5. Corrosion of reinforcement.

The first part of this literature survey will discuss the types of deterioration, their causes, and strategies developed to prevent deterioration.

A literature survey was also performed pertaining to MMFX reinforcing steel. The review was focused on two subjects, the material properties of MMFX steel and its ability to corrode in concrete as compared to uncoated and epoxy coated steels.

2.2.1 Scaling

The flaking of the surface mortar is known as scaling. This can result when concrete cools below the freezing point of water, and the formation of ice crystals in the pore spaces of the concrete create pressures large enough to crack the concrete paste. Scaling allows moisture and chlorides from deicing chemicals to enter into hardened concrete.

The water in pore spaces of the paste does not freeze immediately when the concrete is cooled below 32° F. It has been shown thermodynamically that the freezing temperature in pore spaces depends upon the diameter of the pore. In fact for a 10 nanometer (nm) diameter pore, water will not freeze until 23° F. In a 3.5 nm diameter pore the freezing temperature for water is -4° F (Mindess et al. 2003).

Damage caused by freezing can be caused not only by expansion but by pressures from water and ion migration as water freezes in pore spaces. As ice begins to nucleate in the pore spaces, it increases the concentration of solute in surrounding liquid. Water is drawn from the less dilute solution in the surrounding unfrozen paste in a process known as osmosis. An osmotic pressure is created through this process that causes the paste to crack. Water also moves toward the ice to maintain equilibrium because the relative humidity is lower at the freezing site. This process causes desorption of water out of the surrounding paste, causing it to shrink and crack.

Air entrainment has proved to provide resistance to scaling. The millions of tiny voids created by air entraining admixtures provide space within the paste where water can freeze without damaging the concrete. The water in the air entrained voids will freeze close to 32° F because the volume is much larger than the normal pore spaces. Once ice forms in the air entrained voids, the process of osmosis and desorption can proceed without harm to the concrete (Mindess et al. 2003).

Proper placing, finishing and curing methods are also required to minimize scaling. Excessive vibration or trowling and large amounts of bleeding can also cause scaling. Surfaces subjected to this have a weak layer of paste at the surface or just below that may have microcracks or bleeding channels that transport solutions on the surface to lower levels. Water can penetrate under this weak layer through these microcracks or channels. Freezing of this water will cause scaling of the concrete. Moist curing should follow the finishing process to improve scaling resistance (Mindess et al. 2003).

Scaling can also be minimized by using a low w/cm. A low w/cm results in concrete with lower permeability which restricts the infiltration of water and deicing chemicals.

The use of deicing chemicals containing salt can also cause scaling, even in air entrained concrete. The low vapor pressure of salt solutions cause higher degrees of saturation in the concrete, which in turn cause the voids created by the air entrainer to become saturated also. Because the entrained air voids are filled with water, there is no empty space left in the paste. This situation is only probable where the melt water is not drained away from the exposed deck [(Mindess et al. 2003), (NCHRP 1979)].

2.2.2 Deck Cracking

Cracking is common in concrete because of its relatively low tensile strength and brittle nature. It is an assumption in reinforced concrete theory that the concrete will crack. It is a matter of debate if corrosion of reinforcing causes cracking or cracking causes corrosion. Excessive cracking, especially to the depth of the reinforcement, is detrimental to the structure (Borgard et al. 1987). The causes of cracking are numerous, and often it is not one factor but a combination of factors that cause cracking.

Shrinkage is the leading cause of cracking in concrete decks (Phillips et al. 1997). Shrinkage cracking can lead to water penetration which causes corrosion of the reinforcement and leads to decreased durability. Two types of shrinkage occur, plastic shrinkage and drying shrinkage. Drying shrinkage occurs after the concrete has hardened, while plastic shrinkage occurs in fresh concrete.

Plastic shrinkage occurs in fresh concrete when water is removed from the paste by external means, such as evaporation. Complex systems of menisci form as a result. The menisci cause negative capillary pressures, which causes the paste to contract. The pressures rise until a “breakthrough” pressure is reached (Mindess et al. 2003). At this point the water is no longer evenly distributed. The distribution of water is rearranged to form zones of water with voids in between.

Transverse cracks often form in plastic concrete. These cracks are known as plastic settlement cracks or plastic tension cracks. The concrete settles around the reinforcement after finishing. Since the top reinforcement is transverse these cracks are oriented the same way. The combination of reinforcement size and cover with slump affects the chances of these types of cracks. Table 2.2 shows the probability of this type of cracking with varying slump, cover, and reinforcement size.

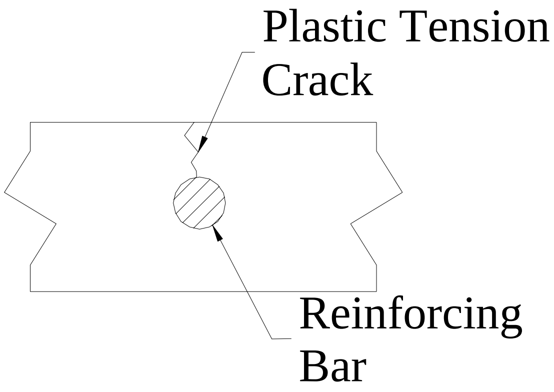
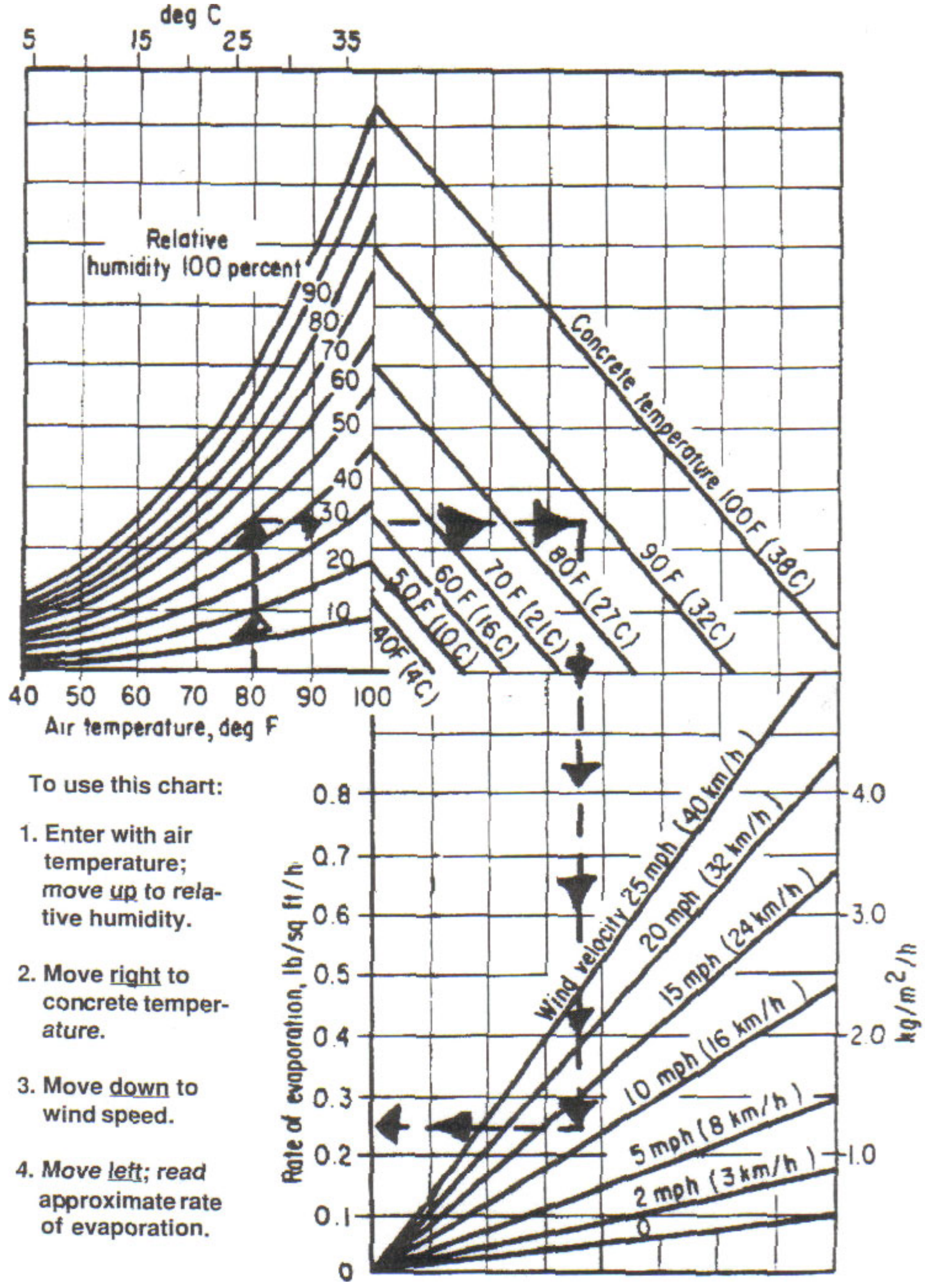


Figure 3: Plastic Tension Crack is Fresh Concrete

Table 2.2 Probability of Plastic Tension Cracks as a Function of Slump, Cover, and Bar Size (Babaei and Hawkins 1987)

	Probability of Cracking (%)								
Slump (in.)	2			3			4		
Bar Size / Cover (in.)	#4	#5	#6	#4	#5	#6	#4	#5	#6
¾	80.4	87.8	92.5	91.9	98.7	100.0	100.0	100.0	100.0
1	60.0	71.0	78.1	73.0	83.4	89.9	85.2	94.7	100.0
1 ½	18.6	34.5	45.6	311	47.7	58.9	44.2	61.1	72.0
2	0.0	1.8	14.1	4.9	12.7	26.3	5.1	24.7	39.0

Plastic shrinkage occurs when the rate of evaporation of moisture from concrete exceeds the rate at which bleed water reaches the surface of the concrete (Babaei and Hawkins 1987). The rate of evaporation is a function of relative humidity, air temperature, concrete temperature, and wind speed. These conditions usually combine to cause plastic shrinkage problems during the summer months. ACI Committee 305 recommends taking precautions against plastic shrinkage when the rate of evaporation exceeds 0.2 lb/ft^2/h (ACI 305R-99). Figure 4 provides an estimation of the rate of evaporation of moisture from concrete.



To use this chart:

1. Enter with air temperature; move up to relative humidity.
2. Move right to concrete temperature.
3. Move down to wind speed.
4. Move left; read approximate rate of evaporation.

Figure 4: Effect of Concrete and Air Temperatures, Relative Humidity, and Wind Speed on the Rate of Evaporation of Surface Moisture from Concrete (ACI 305R-99).

Committee 305 advises scheduling concrete placement at other than normal hours during hot weather conditions. When concrete construction is ongoing with evaporation rates exceed 0.2 lb/ft^2/h, certain placing and curing procedures should be followed. The following are recommendations from ACI Committee 305. Fogging nozzles should be used to cool the air, forms, and reinforcing steel immediately ahead of placement. Fogging nozzles should also be used to maintain a sheen of moisture on the surface after finishing. Temporary windbreaks and shades should also be readily available to protect against sunlight and drying winds.

Moist curing is the best method for reducing early shrinkage cracking. Methods that have been used are ponding, continuous sprinkling, and covering with clean sand kept continuously wet. Other more practical methods include covering the concrete with impervious sheeting or fabric kept continuously wet.

When job conditions do not allow for moist curing liquid membrane-forming compounds are the most practical method of curing. This type of membrane prevents loss of moisture from the concrete. To protect against the sun, heat reflecting white pigmented compounds should be used. These compounds should be applied immediately after the disappearance of the surface water sheen (ACI 305R-99).

Drying shrinkage is the strain caused by the loss of water from the hardened material (Mindess et al. 2003). If the effects of drying shrinkage are not accounted for, the concrete can crack and warp. The most common example of allowances for drying shrinkage is contraction joints. These joints provide a desired location for the concrete to crack.

Reducing the overall water content for the concrete will diminish the chances of drying shrinkage. The overall water content is reduced by lowering the w/cm or the amount of cement. Methods such as reducing the slump, increasing coarse aggregate size, increasing the amounts of aggregate, and placing the concrete at lower temperatures also mitigate drying shrinkage (Babaei and Hawkins 1987).

A certain percentage of reinforcement is also needed as specified by AASHTO (Babaei and Hawkins 1987). The reinforcement helps to counter the affects of drying shrinkage. The reinforcement controls the size of the cracks that do form. It also evenly distributes the cracks. The lengths and widths of shrinkage cracks could become extreme if the reinforcement is placed too deep.

Type K cement was used in shrinkage compensating concrete (SCC) in bridge decks for the Ohio Turnpike Commission (OTC). The OTC constructed 520 bridge decks in a period of 12 years from 1984-1996. The OTC credits shrinkage SCC with reducing early drying shrinkage cracking in its new bridges and bridge deck replacements. The American Concrete Institute (ACI) advises against using SCC on concrete girder bridges because it is thought that they provide external restraint to longitudinal expansion and shrinkage-compensating action (Phillips 1997).

Type K cement increases in volume after the concrete sets. The expansion of the paste offsets the effects of drying shrinkage. The expansion is controlled by the amount of reinforcing used. When the concrete expands the steel is placed in tension and the concrete in compression. The compressive stress generated in the concrete is large enough to overcome the tensile stresses created by drying shrinkage (Mindess et al. 2003).

The amount of expansion before drying is dependent upon the expansive component in the cement (Mindess et al. 2003). The expansive component should be chosen so that the concrete will still be slightly in compression after drying. This net compressive force is very important, because concretes containing type K cement will shrink. The tensile stress created by drying shrinkage will be much less because of net compressive force.

The material properties of the concrete have also been shown to affect cracking. Such properties include slump, water content, cement content, air content, percentage of cement and water (paste), and compressive strength. The effects of these properties on cracking were examined in a study of 40 continuous steel girder bridges in northeast Kansas (Schmitt and Darwin, 1999). The material properties were compared with the crack densities of each bridge deck. Crack densities are the length of crack per area of the deck. The results are shown in Figures 5 – 10.

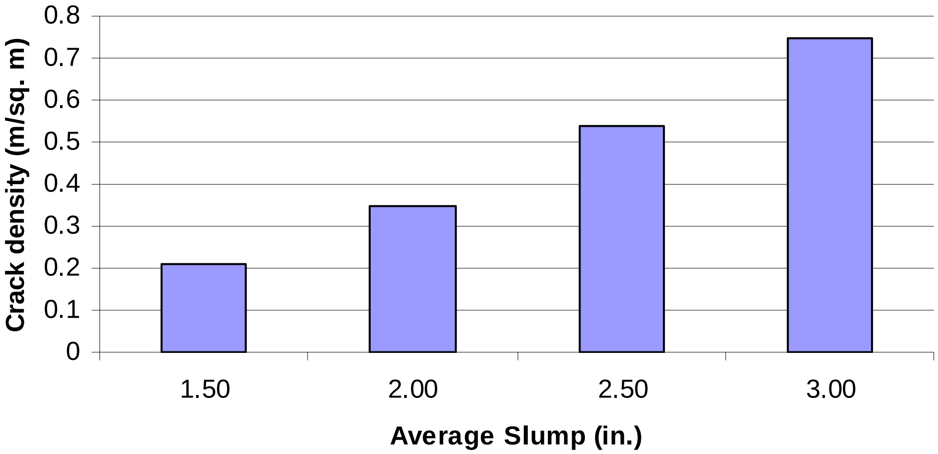


Figure 5: Mean Crack Density versus Slump

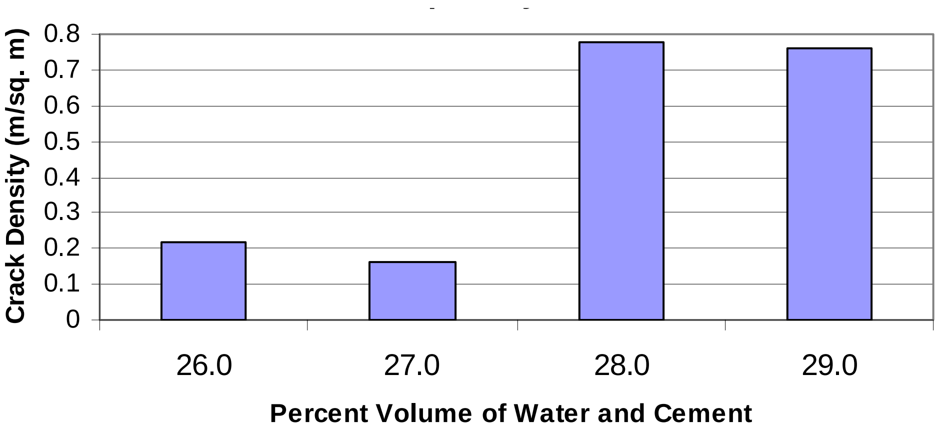


Figure 6: Mean Crack Density versus Percentage of Concrete Volume Occupied by Water and Cement

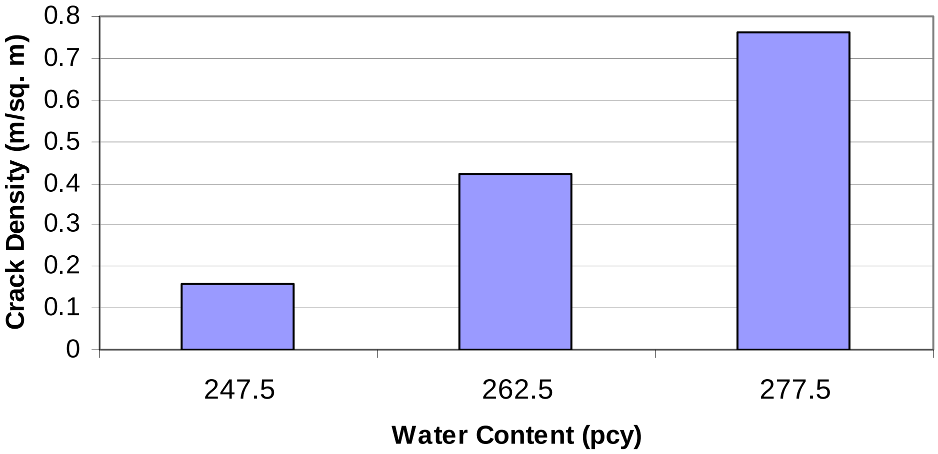


Figure 7: Mean Crack Density versus Water Content

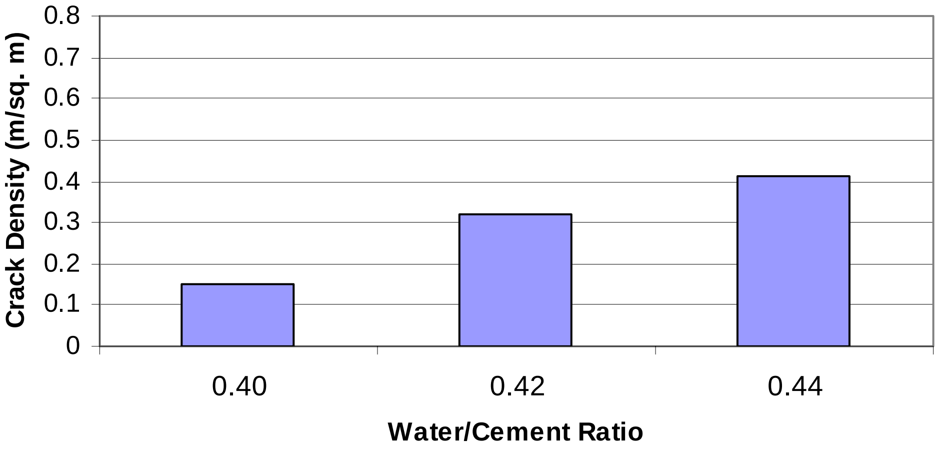


Figure 8: Mean Crack Density versus Water/Cement Ratio

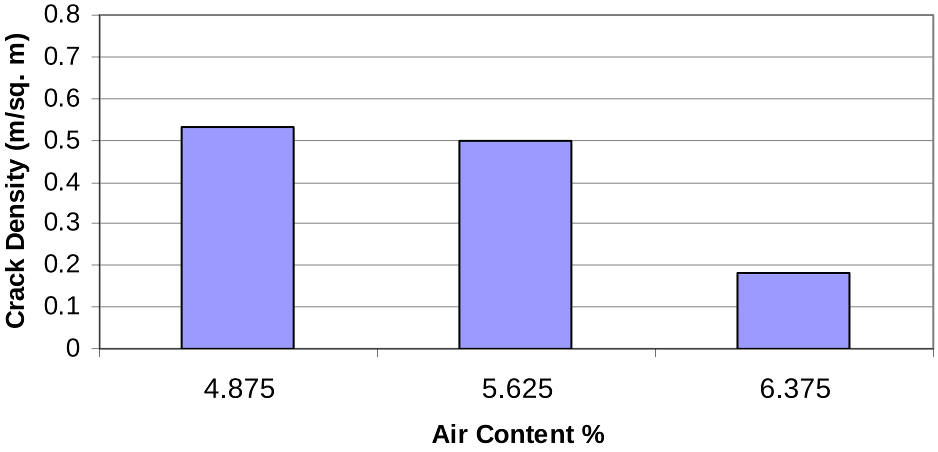


Figure 9: Mean Crack Density versus Air Content

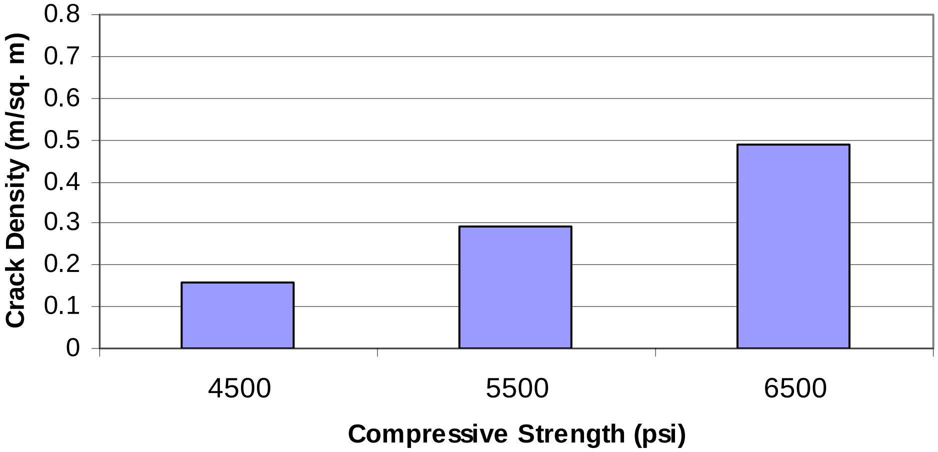


Figure 10: Mean Crack Density versus Compressive Strength

Crack densities were found to be higher with increasing: slump, percent volume of water and cement, water and cement content, and compressive strength. It was also found that when the percent volume of paste was more than 27% the crack densities increased almost 5 fold. Crack densities were found to decrease more than 2.5 times with air contents of 6.0% or greater. The report recommended that the volume of water and cement for bridge decks should not exceed 27.0%. It also recommended that the air content be at least 6.0% for bridge decks.

The traffic on bridges is also a cause for cracking of bridge decks. Vibrations are the product of disturbances caused by vehicles passing over rough or uneven areas, and the deflection immediately under the vehicle. The repetition of vibrations caused by traffic can result in cracking, or increase existing crack widths and depths (Babaei and Hawkins 1987). This type of cracking will understandably increase with the age of the bridge. This type of cracking is also the result of higher traffic speeds and longer spans. This pattern of cracking can be magnified by a large amount of existing transverse cracks, thin flexible decks, light and flexible superstructures, and large amounts of traffic (Ramey et al. 1999).

This situation occurred in several bridge decks in Birmingham, Alabama (Ramey et al. 1999). The bridges were all continuous steel girders built between 1970 and 1972. The cracks were the result of:

1) Early drying and thermal shrinkage;
2) Early concrete-obstructed settlement;
3) Thin and flexible decks (6.5 in.);
4) Light and flexible superstructures, and;
5) Heavy traffic volume (77,000 ADT in 1995).

A large amount of existing transverse cracks grew in width to due increased traffic loadings and abrasion from traffic. The transverse cracks along with longitudinal cracks along the edges of the girders decreased the bending stiffness of the decks, which caused more cracking. These cracks led to spalling of the deck surface, which caused the need for maintenance to patch the decks. It is thought that eventually punching shear failures will result. Punching shear failures result when repetitive loading from traffic weaken the crack surfaces to successfully eliminate aggregate interlock causing the shear strength of the deck to be less than the applied load (Ramey et al. 1999).

2.2.3 Joints in Bridge Decks

Failed or leaking transverse and longitudinal deck joints also decrease the durability of bridges. While a failed joint may not damage the deck in the same manner or severely as cracking or scaling, leaking joints produce serious damage to other components of a bridge. Leaking joints allow chloride laden water to attack and penetrate pier caps, abutments, and girders.

A survey of 21 bridges in Colorado concluded that 18 bridges experienced spalling, cracking, and corrosion in areas immediately below or adjacent to transverse joints. Bridge girders and pier caps were the most commonly damaged elements because of their closeness to the transverse joints. The most common source of the corrosion was attributed to water leaking through the deck joints (Enright and Frangopol 2000).

A Monte Carlo Simulation for Corrosion (MCSC) computer program was used to model the corrosion occurring in a bridge girder over a 90 year period. The MCSC program uses variables from the cross section that include yield strength of the reinforcement, compressive strength of the concrete, initial diameter of the reinforcement, and depth & cover of the reinforcement. The MSCE program also uses variables of the diffusion coefficient, surface and critical chloride concentration, and the corrosion rate. The variables are based on earlier corrosion studies.

Several conclusions were able to be drawn from the results. Corrosion was initiated in a much shorter time for shear reinforcement than for flexural reinforcement. This is due to the smaller cover depth of shear reinforcement. The normalized loss of area was also greater for shear reinforcement than flexural reinforcement. This was attributed to the fact that the time to corrosion was shorter and the diameter of reinforcement is smaller for shear steel.

The normalized rate of loss of shear resistance was found to be lower than the normalized rate of loss of area for shear reinforcement. This was explained by the contribution of the concrete strength to shear resistance. The normalized rate of loss of flexural resistance was found to be about the same as the rate of loss of area for flexural reinforcement.

When the normalized rates of loss for shear and flexural resistance were compared, it was found that the shear resistance decreased at a much faster rate. The previously mentioned survey of 21 bridges had concluded that the most commonly damaged areas were near transverse joints (deck joints). These areas are located near the supports, which are usually the locations of maximum shear. The authors concluded that corrosion causes concrete bridges to be more susceptible to shear failures than any other type of failure (Enright and Frangopol 2000).

2.2.4 Spalling

Cracking and scaling are failures of the concrete due to poor selection of materials, construction procedures, environmental factors, and to a limited extent the design of the structure. In comparison, spalling results from corrosion of reinforcing steel. When the steel begins to corrode it expands in volume. This expansion has been documented from 2.2 to 13 times its original volume (NCHRP 1979). Pressures resulting from corrosion have been reported as high as 4,700 psi (NCHRP 1979), which significantly exceeds the tensile strength of concrete. Once the corroded steel has sufficiently cracked the concrete, sections of the deck can delaminate from the reinforcing. The recurring loading of traffic and the freezing of water in these areas will cause pieces of concrete break loose from the deck.

2.2.5 Corrosion of Reinforcement

The most commonly reported damage to bridges is due to corrosion (Enright and Frangopol 2000), while all of the previously mentioned subjects are sources of bridge deck deterioration. The corrosion of metal in concrete is a topic that has been discussed since the 1940s (Borgard et al. 1989). While corrosion was known to occur in concrete structures, its occurrence was accelerated rapidly in bridge decks by the increased use of deicing salts. Their use in the United States increased by over 600% from the early 1960s to the mid 1970s (NCHRP 1979). Salt is used on roadways and bridges to remove snow and ice because it lowers the freezing temperature of water.

Once a certain concentration of chloride ions is reached, corrosion will begin if there is sufficient oxygen and moisture. The concentration needed has been reported as high as 2.07 lb/cy (NCHRP 1979) and as low as 1.3 lb/cy in an FHWA study (Clear 1974).

Since bridge decks will continue to be treated with deicing salts, different strategies have been developed to slow chloride penetration or prevent corrosion. The strategies include:

1) Increasing cover while lowering the w/cm ratio;
2) Assuring proper consolidation, and;
3) Using epoxy coated reinforcing.

Numerous reports and studies have shown that the chloride content of concrete bridge decks decrease with increasing depth from the surface [(NCHRP 1979), (Babaei and Hawkins 1987), (Clear 1974), (Hasan et al. 1995)]. In FHWA tests of concrete slabs by Clear, ponding of 3% NaCl solution on slabs with only 1 in. of cover initiated corrosion of plain carbon reinforcing steel after only 7 daily pondings (Clear 1974). In the same study none of the black reinforcing steel with a cover of 3 in. corroded after 330 daily pondings. This demonstrates the necessity of providing adequate cover to prevent the reinforcing steel from being exposed to concrete with high chloride concentrations.

The w/cm is also important in reducing chloride penetration. It is commonly accepted that the lower the w/cm, the lower the permeability of the concrete. Research by Clear (1974), (NCHRP 1979) showed the lowest water to cement ratio (w/c) consistently allowed the shallowest penetration. The research measured the chloride content at depths of 1, 2, and 3 in. after 330 daily pondings of 3% NaCl solution. The amount of chloride needed to initiate corrosion (corrosion threshold) was stated to be 1.3 lb/cy in this research.

Concrete with a w/c of 0.50 had average chloride contents of 1.3 lb/cy at a depth of approximately 1.8 in. In contrast, the same average chloride content was found at a depth of approximately 0.9 in. for concrete with a w/c of 0.40. For concrete with a w/c of 0.60, an average chloride content of 1.3 lb/cy was found at a depth 3.0 in.

Low w/cm will do little to decrease permeability if the concrete does not receive adequate consolidation when placed. Clear (1974) found that in concrete with a w/c of 0.32, significant chlorides could permeate to the depth of the reinforcement in slabs that had not been sufficiently consolidated. In a slab with an in place density of 92.5% of the rodded unit weight, corrosion of the reinforcing steel began after 35 daily salt applications. In comparison, a slab consolidated to 97.5% of the rodded unit weight with the same w/c and depth of reinforcing received 313 daily salt applications. This slab had chloride levels at the depth of the reinforcing much less than the amount needed to initiate corrosion.

Epoxy coated reinforcing steel (ECR) was first installed in 1973 as part of the National Experimental and Evaluation Program (NCHRP 1979). There are two models to explain how ECR functions to prevent corrosion. The first suggests that the epoxy is a barricade that prevents the chloride ions from contacting the steel surface. The second model theorizes that the epoxy is a high resistance coating that increases the electrical resistance between adjacent steel reinforcing and helps prevent macro cell corrosion.

For ECR to be effective as a corrosion inhibitor, it must be adhered to the bar. Nicks and cuts in the epoxy coating can result from transportation and handling of the ECR. Increasing the amount of supports during shipping can prevent the bars from rubbing together and damaging the coating. Proper handling of the reinforcement prior to and during placement is also important to prevent damage to the coating. Nylon ropes should be used to bundle the bars, and nonmetallic ties and chairs should be used to prevent electrical connection between the mats of steel in the deck. If proper procedures are used, this type of damage can be minimized.

Laboratory testing of ECR has shown that it is very effective in preventing corrosion. In FHWA tests by Virmani and Clear (Babaei and Hawkins 1987) the coating was purposely damaged to beyond that which frequently occurs in handling. It was estimated that for a given chloride exposure in a bridge deck the quantity of the damaged ECR consumed in the top mat in 12 years is equal to amount of uncoated steel consumed in the top mat in 1 year (Babaei and Hawkins 1987). The results were explained by the high electrical resistance created by the epoxy coating. An electrical circuit may occur between the top and bottom mats of steel, but because the high overall resistance of the circuit only a very small current can flow. In this manner ECR is effective at mitigating macro cell corrosion.

A long term study of ECR was conducted by Scannell and Clear for more than 6.5 years (Scannell and Clear 1990). Slabs were cast with ECR in the top mat only, ECR in both mats, and black steel in both mats. The slabs were ponded with a 3% sodium chloride solution for 3 years. The ECR mats had considerably lower macro cell current readings compared to the black steel mats. The macrocell currents for slabs with black steel in both mats were routinely 40 times higher than those containing ECR in only the top mat, and 100 times higher than the slabs containing ECR in both mats. The chloride content at the top bar location was more than 10 lb/cy after 3 years of ponding.

The resistance between the top and bottom mats was also measured. Average resistances of more than 2000 ohms were measured for slabs with epoxy coated reinforcing in only the top mat. Average resistances of 1900 ohms were measured for slabs with epoxy coated reinforcing in both mats. Compared with an average resistance of 22 ohms for slabs with black steel in both mats, this indicates that the epoxy coating increased considerably the resistance of the macro cell that had formed. The high resistances for epoxy coated reinforcement show that there was no trend for the coating to deteriorate in chloride contaminated concrete.

Overall, this study showed the effectiveness of ECR to prevent corrosion. When the ECR was removed from the slabs at the end of testing the coating was still adhered to the steel, but it had softened some. It was noted that this made it easier to remove the epoxy coating.

This finding coincides with the conflicting reports about ECR performance in service. Signs of corrosion were reported in the Long Key Bridge in Florida only 6 years after its construction. In a study of 30 bridge substructures in the marine environments of Florida, 29 showed signs of debonding of the epoxy coating (Weyers et al. 1997). The bridges were at least 4 years old. Although the epoxy had debonded, there were no signs of corrosion.

A two part study of Virginia bridge decks showed similar signs of debonding of the epoxy coating (Pyc et al. 2000). The first part of the study dealt with three 17 year old bridge decks constructed with ECR in the top mat (Weyers et al. 1997). Twelve cores were taken from each bridge. The epoxy coating was debonding or had debonded in most of the ECR in the cores. The study estimated that it was probable that the epoxy coating would begin to debond in 15 years for Virginia bridges. It was concluded that chlorides arrived at the level of ECR before the epoxy debonded in only 5% of Virginia bridge decks. In the other 95% of bridge decks the epoxy debonds before the chlorides arrive at the level of the ECR. Debonding of the epoxy from the reinforcement renders ECR useless to mitigate corrosion. Once the epoxy debonds, chlorides can easily attack the steel.

In the second part of the study 250 cores were taken from 18 bridge decks. The age of the bridge decks ranged from 2 to 20 years. In all decks older than 4 years, except for one, the epoxy coating was debonding. Visible signs of corrosion were present under the epoxy coating.

In contrast, a study of 6 Indiana bridges built from 1976 to 1985 with moderate to severe applications of deicing salts produced no findings of failed ECR (Hasan et al. 1995). Inspection of ECR removed from cores showed no signs of corrosion or debonding of the epoxy coating. It was reported that “the coating was difficult to remove with a knife”. Four of the six bridges had chloride contents above the “threshold level” of 2.0 lb/cy.

The question of whether or not ECR provides effective protection against corrosion is uncertain. It is thought that the loss of adhesion of the epoxy coating is due to the oxides and impurities present on the steel. A layer of ferric oxide remains on the steel even after it is cleaned before it is coated with epoxy. The epoxy must bond to this layer of ferric oxide. A relative humidity of 60% and temperature of 68°F or greater has been shown to considerably increase the rate of debondment of epoxy from ferric oxide (Pyc et al. 2000). Also a relative humidity of 70% in the concrete is necessary for corrosion of the reinforcement (Pyc et al. 2000). Thus prolonged exposure to wetting and drying cycles and warm, moist, humid, and salty environments are also thought to contribute to the debonding and corrosion of the epoxy coating [(Hasan et al. 1995), (Weyers et al. 1997)].

2.3 MMFX Microcomposite Steel

MMFX Microcomposite Steel is a proprietary product of MMFX Steel Corporation, a subsidiary of MMFX Technologies Corporation. MMFX claims that its steel differs from regular carbon steel in its microstructure. Normal carbon steel contains carbide and ferrite which form galvanic cells. These become microgalvanic cells in a corrosive setting, which are the cause of corrosion. MMFX claims that their microstructure prevents corrosion from being initiated because it is carbide free. It also claims that its laminated microstructure not only increases corrosion resistance, but also increases strength, ductility, toughness, fatigue resistance, brittle fracture, and cold formability (MMFX Steel Corporation 2004). The chemical composition and minimum material properties reported by MMFX are shown in Table 2.3 and 2.4 respectively.

Table 2.3 Maximum Percentages (by weight) of Elements in MMFX Steel (MMFX Steel Corporation 2004)

Carbon	Chromium	Manganese	Nitrogen	Phosphorus	Sulfur	Silicon
0.10%	8 – 10%	1.5%	0.05%	0.02%	0.025%	0.5%

Table 2.4 Minimum Material Properties of MMFX Steel (MMFX Steel Corporation 2004)

Yield Strength at 0.2% offset (ksi)	Tensile Strength (ksi)	Strength equal to strain of 0.0035 in/in (ksi)
100	150	80

The remainder of this literature review will discuss published research reports of MMFX's material properties and its purported ability to resist corrosion as compared to other reinforcing steels.

2.3.1Fundamental Material Properties of MMFX Steel Rebars by El-Hacha and Rizkalla, North Carolina State University

A series of tension tests were performed in order to find modulus of elasticity, yield strength, ultimate strength, and their respective strains (El-Hacha and Rizkalla 2002). Yield strength was calculated from the 0.2% offset method since there was no defined yield point. Yield strength was also calculated at 0.7% strain in accordance with ASTM A722 because of the high strength of the bars. The sizes of reinforcing bars tested were: #4, #6, and #8. Test specimens were loaded in a universal testing machine. The elongation was measured by an extensometer and electrical resistance strain gauges. Five specimens were tested for each size reinforcing bar. The averaged results are summarized in the following three tables.

Table 2.5 Average Results for #4 MMFX Reinforcing Bar (El-Hacha and Rizkalla 2002)

Elastic Modulus (ksi)	**Yield Strength (ksi)**		**Strain at 0.2% offset yield (in/in)**	**Ultimate Strength (ksi)**	**Strain at ultimate strength (in/in)**
	0.2% offset	0.7% strain			
29,000	116.0	121.34	0.006093	165.26	0.044075

Table 2.6 Average Results for #6 MMFX Reinforcing Bar (El-Hacha and Rizkalla 2002)

Elastic Modulus (ksi)	**Yield Strength (ksi)**		**Strain at 0.2% offset yield (in/in)**	**Ultimate Strength (ksi)**	**Strain at ultimate strength (in/in)**
	0.2% offset	0.7% strain			
29,000	119.91	125.03	0.006272	175.99	0.053405

Table 2.7 Average Results for #8 MMFX Reinforcing Bar (El-Hacha and Rizkalla 2002)

Elastic Modulus (ksi)	**Yield Strength (ksi)**		**Strain at 0.2% offset yield (in/in)**	**Ultimate Strength (ksi)**	**Strain at ultimate strength (in/in)**
	0.2% offset	0.7% strain			
29,000	118.35	124.44	0.006123	176.41	0.055212

2.3.2 MMFX Steel Testing Program, Sponsored by MMFX Steel Corporation

MMFX Steel employed the services of several consulting engineers and independent testing laboratories between November 2000 and April of 2001 to analyze among other things, the material properties of the first series of MMFX steel melts. A report of the findings was published by MMFX Steel Corporation in October of 2001 (MMFX Steel Corporation 2001).

Tension tests of 24 machined reduced section #6 MMFX reinforcing bars were conducted by Bodycote Metal Technology in November, 2000. The yield strength at a 0.2% offset was reported as 126.5 ksi. The ultimate strength was reported as 185 ksi.

Tension tests of 9 machined reduced section #6 MMFX reinforcing bars were conducted by Durkee Testing Laboratories in December, 2000. The yield strength at a 0.2% offset was reported as 126.5 ksi. The ultimate strength was reported as 184 ksi.

Twining Laboratories conducted two tension tests of as received #6 MMFX reinforcing bars in December, 2000. The estimate of yield strength at a 0.2% offset was reported as 132.5 and 127.7 ksi (MMFX Steel Corporation 2001).

Dr. Kenneth Vecchio at the University of San Diego conducted 10 tensile tests of two in. reduced section #6 MMFX reinforcing bars in April 2001. The yield strength at 0.2% offset was reported as 127.5 ksi. The ultimate strength was reported as 183.4 ksi and the elastic modulus was reported as 30.14 Msi.

Finally Modern Industries, Inc. conducted tensile tests of as received #5, #8, and #9 MMFX reinforcing bars. Twenty #5 bars, three #8 bars, and twenty #9 bars were tested. The average yield strengths at a 0.2% offset were reported as follows: #5 – 130.5 ksi, #8 – 127.3 ksi, #9 – 127.3 ksi. The average ultimate strengths were reported as follows: #5 – 178.5 ksi, #8 – 182.6 ksi, #9 – 182.0 ksi.

2.3.3 Mechanical and Corrosion Properties of a High Strength, High Chromium Reinforcing Steel for Concrete by Darwin, Browning, Nguyen, and Locke, University of Kansas Center for Research

This report investigated the material and corrosion properties of MMFX reinforcing steel for the South Dakota Department of Transportation (SDOT) (Darwin et al. 2002). Tension tests of MMFX reinforcing bars were conducted in order to obtain yield strength, ultimate strength, and percent elongation. Three tests were used to measure the corrosion rate of MMFX steel as compared to ECR and plain carbon steel. The tests conducted were the Rapid Macrocell Test, the Southern Exposure Test, and the Cracked Beam Test.

2.3.3.1 Tests of Material Properties

Tensile tests were conducted on five #5 and 10 #6 MMFX reinforcing bars. Five of the #6 bars were from the same heat as the #5 bars. The results are summarized in Table 2.8.

Table 2.8 Material Properties of MMFX Reinforcing Bars (Darwin et al. 2002)

Heat No.	Size	Average Yield Strength (ksi)		Average Ultimate Strength (ksi)	% Elongation in 8 in.
		0.2% offset	0.7% offset		
810737	# 5	119.6	120.9	160.2	7.2
810737	# 6	141.6	142.7	173.1	7.0
710788	# 6	132.5	135.1	164.6	7.1

The report concluded that MMFX steel demonstrates yield strengths equal to twice the requirements for Grade 60 reinforcing steel. The average elongations meet the minimum requirement for ASTM A 615 Grade 75 reinforcement. Also, if the yield strength is based on 0.7% strain, MMFX reinforcing bars meet the requirements of ASTM A 722 for steel bars for prestressed concrete.

2.3.3.2 Corrosion Tests Performed

The Rapid Macrocell Test consist of placing the test specimen, a bare or mortar wrapped reinforcing bar, in a container containing a simulated pore solution containing 0.095 lb of sodium chloride per quart of solution. Two other specimens are placed in a separate container with a simulated pore solution containing 0.034 lb of potassium hydroxide and 0.037 lb of sodium hydroxide per quart of solution. Crushed mortar fill is added to the containers with mortar wrapped bars to simulate actual concrete. Three inches of each bar is placed below the simulated pore solutions. The specimen in the solution with sodium chloride is the anode, while the other two specimens in the KOH & NaOH are the anode.

A salt bridge connects the solutions in the two separate containers. The anode and cathode are connected by a 10 ohm resistor. Air that has been scrubbed to remove carbon dioxide is bubbled into the container with the cathode. This is done to ensure an adequate supply of oxygen. An illustration of the test setup is shown in Figure 11. The rapid macrocell test program is shown in Table 2.9.

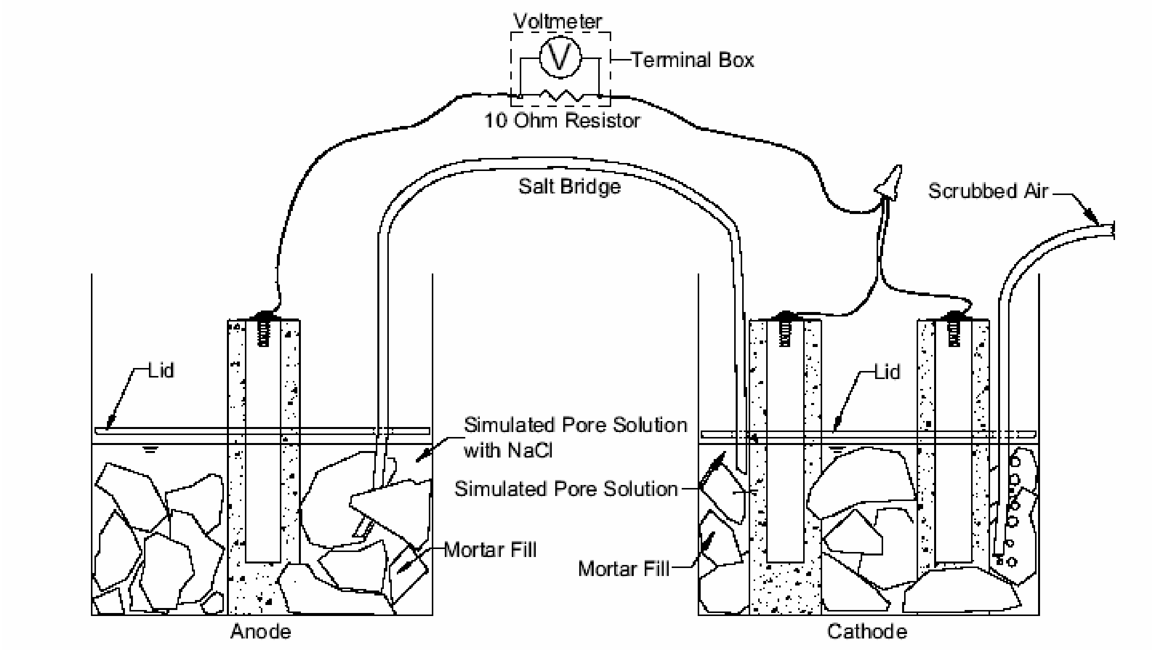


Figure 11: Test Setup for Rapid Macrocell Test (Darwin et al. 2002)

Table 2.9 Rapid Macrocell Test Program (Darwin et al. 2002)

Steel Designation	Heat No.	NaCl concentration	# of Tests	Notes
Bare Specimens				
N3[1]	S44407	1.6 m	6	
MMFX(1)[2]	810737	1.6 m	6	Lid above bars
MMFX (2)	810737	1.6 m	6	
MMFXs	810737	1.6 m	6	Sandblasted bars
MMFXb	810737	1.6 m	3	Bent bars at anode
MMFX#6(1)	810737	1.6 m	3	
MMFX#6(2)	710788	1.6 m	3	
N2h[1]	K0-C696	6.04 m	5	
MMFXsh	810737	6.04 m	6	Sandblasted bars
Mortar-wrapped specimens				
N3m	S44407	1.6 m	6	
MMFXm	810737	1.6 m	6	
ECRm[3]	S44407	1.6 m	6	
MMFX/N3	810737/ S44407	1.6 m	3	Anode/cathode
N3/MMFX	S44407/810737	1.6 m	3	Anode/cathode

[1] N2 and N3: Conventional, normalized A 615 reinforcing steel
[2] MMFX: MMFX Microcomposite steel
[3] ECR: Epoxy coated N3 steel with four 1/8 in. holes in coating

The macrocell current can be determined by measuring the voltage across the resistor and dividing it by the resistance. The macrocell current is then used to calculate the corrosion rate. The corrosion potential of the anode and cathode are also measured using a saturated calomel electrode.

The results of the Rapid Macrocell Test for bare specimens showed that with the exception of the #6 MMFX bars, MMFX steel corroded at a lower rate than conventional steel. The 24 specimens with #5 MMFX bars corroded at an average rate of 13.3 μm/yr. This was equal to 37% of the corrosion rate of the conventional steel (35.6 μm/yr). The 24 specimens with #5 MMFX bars had an average total corrosion loss of 3.1 μm. This is equal to 34% of the average total loss of the conventional steel (9.0 μm). The specimens with #6 MMFX bars corroded at an average rate of 26 μm/yr. This rate is equal to 81% of the conventional steel corrosion rate.

The sandblasted bars (MMFXsh) initially corroded at approximately half the rate of conventional steel. However, after seven weeks the two steels began to corrode at about the same rate, 40 μm/yr. The average corrosion loss of the sandblasted MMFX bars was 10.9 μm, or 87% of the conventional steel loss. These tests were conducted at higher chloride concentrations (6.04 m). The results indicate that MMFX steel will corrode at similar rates to conventional steel at high chloride concentrations.

The ECR showed the lowest corrosion rate for mortar wrapped specimens. The rate was 4.2 μm/yr. It was stated that had the epoxy not been penetrated, corrosion would have not been measurable on the ECR. MMFX steel had the next lowest corrosion rate of mortar wrapped specimens, at 10.5 µm/yr. Conventional steel had the highest corrosion rate of 17.6 µm/yr at the end of the test.

The tests with macrocells of MMFX and conventional steel, showed corrosion rates in between the other specimens. The specimens with conventional steel at the anode and MMFX steel at the cathode had a corrosion rate of 12 µm/yr. The specimens with MMFX steel at the anode and conventional steel at the cathode had slightly higher corrosion rates. These results showed that when the steels were combined in reduced the performance of MMFX steel.

The Southern Exposure Test creates a highly corrosive environment meant to simulate 30 to 40 years of exposure for bridge decks. The test consists of making small slab with two layers of reinforcing steel. A dam is cast with the slab to hold a 15% sodium chloride solution for ponding. The slab is sealed with an epoxy concrete sealer and a 10 ohm resistor is connected between the two layers of reinforcing steel. The slabs are ponded for 4 days at 68-84° F and dried for 3 days at 100° F for 12 weeks. The slabs are then ponded continuously for 12 weeks. The entire process is then repeated for a total of 96 weeks.

Macrocell current and corrosion rates are determined from the voltage measured across the resistor. Corrosion potentials are also measured for the top and bottom layers of reinforcing. The resistance between the two layers of reinforcing is also measured. A drawing of the test setup for the Southern Exposure Test is shown below in Figure 12. The southern exposure test program is summarized in Table 2.10.

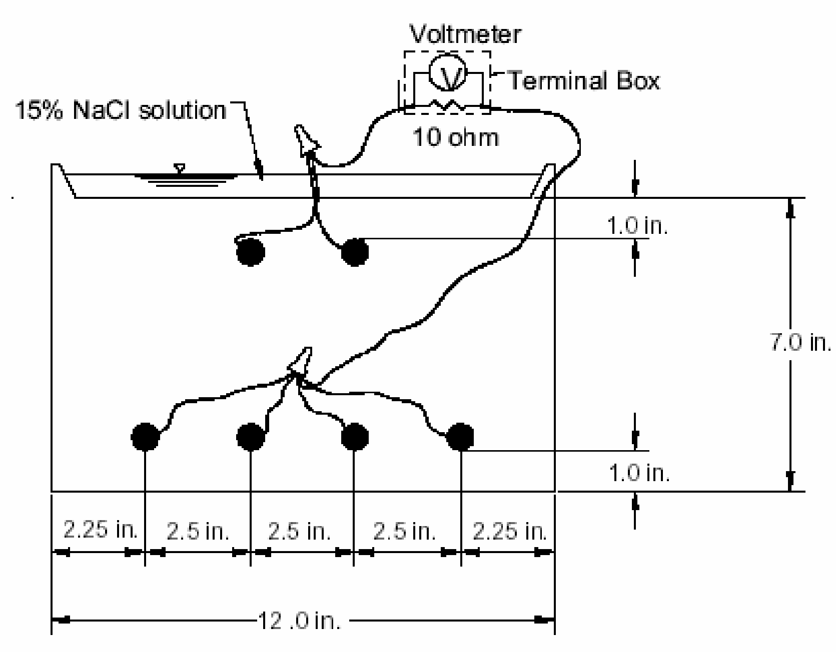


Figure 12: Test Setup for Southern Exposure Test (Darwin et al. 2002)

Table 2.10 Southern Exposure Test Program (Darwin et al. 2002)

Steel Designation	Heat No.	# of Tests	Notes
N3(1)[1]	S44407	4	
N3(2)	S44420	2	
MMFX[2]	810737	6	
MMFXb	810737	3	Bent bars at anode
MMFX/N3	810737/S44420	3	MMFX top bars
N3/MMFX	S44420/810737	3	N3 top bars/MMFX bottom
ECR(1)[3]	S44407	4	
ECR(2)[3]	S44420	2	

[1] N2 and N3: Conventional, normalized A 615 reinforcing steel
[2] MMFX: MMFX Microcomposite steel
[3] ECR: Epoxy coated N3 steel with four 1/8 in. holes in coating

The chloride content of the concrete was measured in the southern exposure specimens when the corrosion potential dropped below -350 mV. The chloride content was measured as a percent of concrete weight on and acid-soluble and water-soluble basis. The acid-soluble chloride content was measured in conformance with Procedure C of AASHTO T 260-94. The water-soluble chloride content was measured in conformance with Procedure A of AASHTO T 260-97.

Chloride contents were converted from the percent of concrete weight to weight concentrations per cubic yard. A concrete unit weight of 3777lb/cy was used for the calculations. The chloride content needed to initiate corrosion in conventional steel was found to be 1.04 lb/cy on an acid soluble basis and 0.94 lb/cy on a water-soluble basis. For MMFX steel the chloride content needed was found to be 3.60 lb/cy on an acid soluble basis and 3.32 lb/cy on a water-soluble basis.

The results of the Southern Exposure Test showed that the 3 specimens with bent MMFX bars were corroding at the highest rate, 7.1 μm/yr. The specimens with conventional steel in the top and MMFX in the bottom showed the next highest corrosion rate, 5.3 μm/yr. Specimens with all conventional steel showed average corrosion rates of 4.8 μm/yr. The all MMFX steel specimens showed corrosion rate of 0.6 μm/yr. The lowest corrosion rates were exhibited by ECR and MMFX steel in the top combined with conventional steel in the bottom. These specimens showed a corrosion rate of 0.01 μm/yr.

The Cracked Beam Test models the exposure of reinforcing to chlorides that enter the concrete through cracks. The test consists of making a specimen half the width of the Southern Exposure slab, with one reinforcing bar in the top, and two in the bottom. A crack is replicated by inserting a 0.012 in. stainless steel shim into the fresh concrete directly above the top reinforcing bar. The shim is removed within 24 hours of casting. The beam is exposed to the same wetting and drying periods as the Southern Exposure

Test. A drawing of the Cracked Beam Test is shown below in Figure 13. The test program for the cracked beam test is shown in Table 2.11.

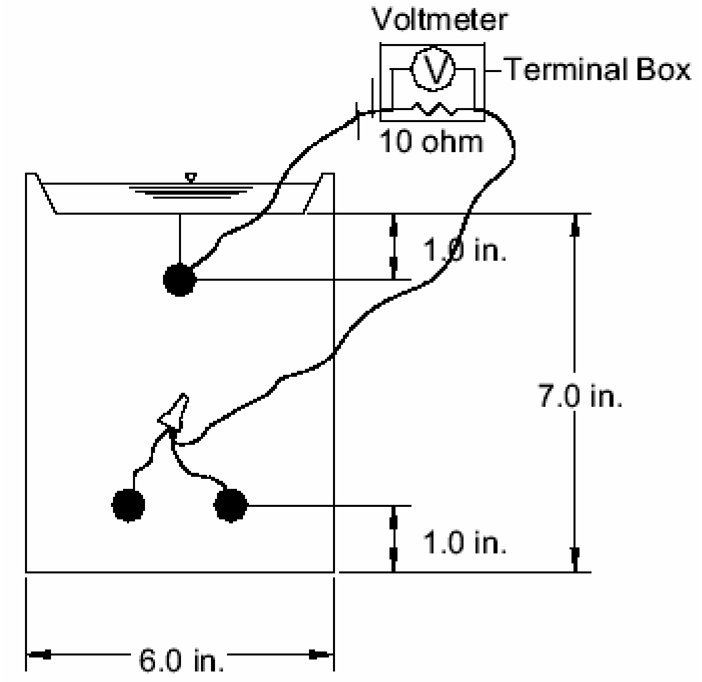


Figure 13: Test Setup for Cracked Beam Test (Darwin et al. 2002)

Table 2.11 Cracked Beam Test Program (Darwin et al. 2002)

Steel Designation	Heat No.	# of Tests
N3(1)[1]	S44407	4
N3(2)	S44420	2
MMFX	810737	6
ECR(1)[2]	S44407	4
ECR(2)	S44420	2

[1] N2 and N3: Conventional, normalized A 615 reinforcing steel
[2] ECR: Epoxy coated N3 steel with four 1/8 in. holes in coating

The results of the Cracked Beam Test showed that conventional steel displayed the highest average total corrosion loss, 4.4 μm. MMFX steel showed an average total corrosion loss of 1.7 μm. ECR showed an average total corrosion loss of 0.3 μm. The six specimens containing ECR had a total corrosion loss equal to 7.5% of the loss shown by conventional steel. MMFX steel had a total corrosion loss equal to 37% of the loss shown by conventional steel.

With respect to the corrosion properties of MMFX steel, the report's conclusions are as follows. The chloride content necessary to initiate corrosion in MMFX steel is roughly four times that of conventional carbon steel. MMFX steel was found to corrode at a rate between one-third and two-thirds of conventional reinforcing. The corrosion rate of ECR was lower than MMFX in all three corrosion tests. The report's conclusion was that ECR's corrosion performance was superior to that of MMFX steel. The recommendation to SDOT was to not use of MMFX reinforcing steel in its bridge decks.

2.3.4 Investigation of the Resistance of Several New Metallic Reinforcing Bars to Chloride-Induced Corrosion in Concrete by Clemeña, G.G., Virginia Transportation Research Council (VTRC)

This report was conducted for the Virginia Department of Transportation (VDOT) in order to compare the corrosion properties of new types of reinforcing bars that could be more durable than ECR (Clemena 2003). The types of reinforcing tested were stainless steel-clad carbon steel bars (316L), MMFX steel, a "lean" duplex stainless steel called 2101 LDX, and a carbon steel bar coated with a 2-mil layer of arc-sprayed zinc and then epoxy. Two different stainless steel bars, 304 and 316LN, and an A 615 carbon steel bar were also used for a comparison.

The reinforcement was cast into concrete blocks like the ones shown in Figures 14 and 15. The blocks were coated with epoxy approximately weeks after casting. They were then ponded with a sodium chloride solution for 3 days and allowed to dry for 4 days. 3.0 mm wide holes or 25 mm cuts were made on some of the bars with stainless steel cladding to simulated defects in the cladding. A 25 mm cut was made on some of the zinc/epoxy combination coated bars. This cut went through both the zinc and epoxy on some bars and on others it only went through the epoxy.

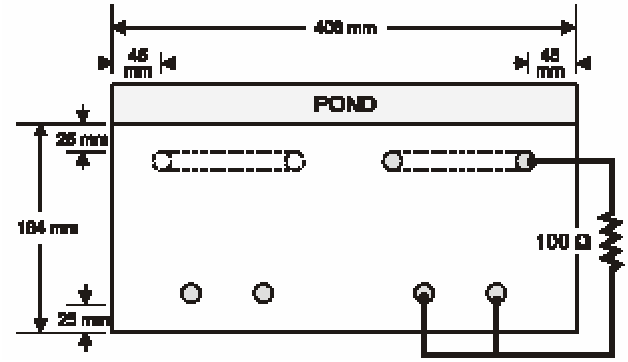


Figure 14: Side View of Test Setup for VTRC Corrosion Tests (Clemena 2003)

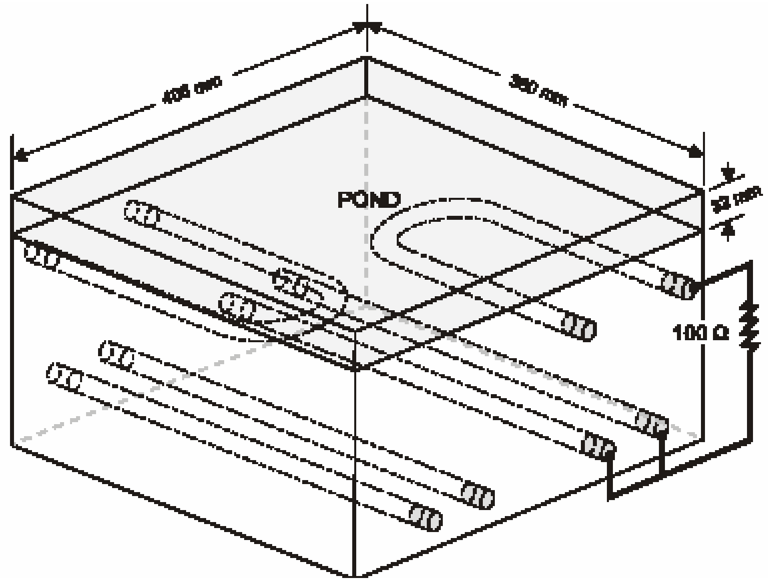


Figure 15: Three Dimensional View of Test Setup for VTRC Corrosion Tests (Clemena 2003)

Voltage readings were taken across the resistor between the top and bottom layers of reinforcing. These voltage readings were used to calculate the macrocell current. Corrosion potentials for the top layer of reinforcing were measured with a $Cu/CuSO_4$ reference electrode. The acid soluble chloride content was also measured in 16 of the blocks. The estimated time until corrosion was initiated for each type of reinforcement is shown in Table 2.12

Table 2.12 Estimated Time to Corrosion for Different Types of Reinforcement (Clemena 2003)

Reinforcement	Estimated Time to Corrosion (days)
Plain Carbon Steel	92
2101 LDX	147
MMFX	245
Zinc/Epoxy Coated w/cut through both	532
Zinc/Epoxy Coated w/cut through epoxy	637
Zinc/Epoxy Coated w/ no damage	>735*
316 L Stainless Steel Clad	>1,082*
316 L Stainless Steel Clad w/holes	>1,082*
316 L Stainless Steel Clad w/cut	392
314 (Solid Stainless)	>1,082*
316 LN (Solid Stainless)	>1,082*
*Test not complete.	

The estimated concentration of chloride needed to initiate corrosion was calculated from the acid soluble chloride contents measured in the concrete blocks. The concentration needed for each bar can be expressed as a ratio between the respective bar and a plain carbon steel bar. The ratio for the plain carbon steel bar is then 1.0. The ratios for each bar are shown in Table 2.13.

Table 2.13 Ratio of Chloride Content Needed to Initiate Corrosion for Different Reinforcement In Comparison to Plain Carbon Steel (Clemena 2003)

Reinforcement	Ratio
Plain Carbon Steel	1.0
2101 LDX	2.6-3.7
MMFX	4.6-6.4
Zinc/Epoxy Coated w/cut	7.7-10.4
Zinc/Epoxy Coated	>8.9*
316 L Stainless Steel Clad w/ cut	6.5-8.8
316 L Stainless Steel Clad	>10.4*
314 (Solid Stainless)	>10.4*
316 LN (Solid Stainless)	>10.4*
*Test not complete.	

The report ranked the types of reinforcement based upon their resistance to corrosion from least effective to most effective.

Table 2.14 Ranking of Resistance to Corrosion of Reinforcing Steels (Clemena 2003)

Reinforcement	Resistance to corrosion*
Plain carbon steel	1
2101 LDX	2
MMFX	3
Zinc/Epoxy Coated	4
316 Stainless Steel Clad	5
304 Solid Stainless	6
316 LN Solid Stainless	7
* 1 is least effective, 7 is most effective.	

The relative rankings of the last four types were not clear since the testing was not complete. It was emphasized that the last four types were much more effective at resisting corrosion than MMFX and 2101 LDX reinforcing.

The report recommended VDOT consider using MMFX, 2101 LDX, or the zinc/epoxy coated steel for heavily salted bridges. It also recommended that VDOT should use MMFX, zinc/epoxy coated steel, or continue using ECR for low volume bridges that are not heavily salted.

3. EXPERIMENTAL PROGRAM

3.1 Objectives of Experimental Program

MMFX and IPANEX both claim to help improve concrete durability by minimizing or slowing corrosion. The objectives of the experimental program are to evaluate these claims. The properties of concrete cast with IPANEX and MMFX steel must also be evaluated if they are to be used. The objectives of the experimental program are outlined below.

1) Comparison between MMFX and epoxy coated steel in the ability to form macrocells by testing in conformance with ASTM G 109;

2) Evaluation of IPANEX's ability to mitigate or diminish macrocell corrosion by testing in conformance with ASTM G 109;

3) Compare differences in the material properties of MMFX steel and Grade 60 steel;

4) Evaluation of IPANEX's effect on chloride permeability of concrete in conformance with ASTM C 1202, and;

5) Comparison of fresh and hardened properties of concrete made with and without IPANEX.

3.2 Scope of Experimental Program

There were five tests conducted in the experimental program. These tests were selected based upon the objectives of the experimental program. Table 3.1 shows the designation and test method of each test.

Table 3.1 Designation and Test Method of Tests in Experimental Program

Designation	Test Method
ASTM G 109-99	Determining the Effects of Chemical Admixtures on the Corrosion of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments
Tension Tests	Mechanical Testing of Steel Rebar
ASTM C 39/C 39M-01	Compressive Strength of Cylindrical Concrete Specimens
ASTM C 1202-97	Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
ASTM C 469-94	Static Modulus of Elasticity of Concrete In Compression

The properties measured in the experimental program are shown below. The properties can be grouped together in five main categories. Slump, unit weight, air content, and compressive strength of field cast cylinders were measured by the ODOT.

1) Fresh Concrete Properties
    - Slump (ODOT)
    - Unit Weight (ODOT)
    - Air Content (ODOT)
2) Hardened Concrete Properties
    - Compressive Strength of Field Cast Cylinders (ODOT)
    - Compressive Strength of Cores from Bridge Decks (ASTM C 39)
    - Elastic Modulus (ASTM C 469)

3) Material Properties of Reinforcing Steel (Tension Tests)
    - Elastic Modulus
    - Yield Strength
    - Ultimate Strength
4) ASTM G 109
    - Macrocell Current
    - Corrosion Potential
    - Total Corrosion
5) ASTM C 1202
    - Resistance to Penetration of Chloride Ions

3.3 Research Variables

There were four variables evaluated in the experimental program.

1) Type of reinforcing (uncoated, epoxy coated, or MMFX steel);
2) w/cm (0.40, 0.44, 0.48);
3) with IPANEX or without IPANEX, and;
4) Chloride content (0, 2, 5 lb/cy).

ASTM G 109 was employed to evaluate the effects that the different variables had on corrosion. Tension tests evaluated the material properties of MMFX steel vs. Grade 60 reinforcement. ASTM C 39 evaluated the effect IPANEX has on compressive strength. ASTM C 1202 evaluated the effect IPANEX has on the chloride permeability of concrete. ASTM C 469 evaluated the effect IPANEX has on the elastic modulus of concrete. The effect of IPANEX has on the fresh properties of slump, air content, and unit weight was evaluated from ODOT field records.

These variables were evaluated by the properties measured in the experimental program. The test or procedure used in the experimental program, properties measured by the test or procedure, and the variable evaluated by the properties are shown in Table 3.2.

Table 3.2 Variables Evaluated by the Properties Measured in Each Test or Procedure of the Experimental Program

Test or Procedure	Variables	Properties Measured
ASTM G 109-99	Type of reinforcing, w/cm, IPANEX, and chloride content	Macrocell current, corrosion potential, and total corrosion
Tension Tests	Type of reinforcing	Yield strength, ultimate strength, and elastic modulus
ASTM C 39/C 39M-01	IPANEX vs. non-IPANEX	Compressive strength
ASTM C 1202-97	IPANEX vs. non-IPANEX	Chloride permeability
ASTM C 469-94	IPANEX vs. non-IPANEX	Elastic modulus
Evaluation of ODOT Field Records	IPANEX vs. non-IPANEX	Slump, air content, unit weight, and compressive strength

3.4 ASTM G 109-99 Standard Test Method for Determining the Effects of Chemical Admixtures on the Corrosion of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments

This procedure is used to evaluate materials intended to inhibit chloride induced corrosion of steel in concrete. G 109 evaluates the ability of various materials to resist corrosion by measuring the macrocell current and the corrosion potential.

3.4.1 Design of Variable Combinations for ASTM G 109

All four variables were evaluated using ASTM G 109. Three types of reinforcing steel, three w/cm, three amounts of chloride ($CaCl_2$), with IPANEX and non-IPANEX concrete produced 54 different combinations. In order to reduce the number of specimens that needed to be made and still be able to obtain meaningful results, DOE KISS computer software was used.

DOE KISS stands for ”Design of Experiments Keep It Statistically Simple”. DOE KISS is a multiple regression software tool that runs in Microsoft Excel. DOE KISS allows computer aided and non computer aided design of experiments. Based upon the number of variables a Taguchi L18 design was selected. A design matrix was created by using the L18 design and the variables. The matrix assigned values of -1 for the lowest parameter and +1 for the highest parameter. The design matrix is shown in Table 3.3. The explanation of the coding is shown in Table 3.4.

Table 3.3 Design Matrix from DOE KISS for G 109

	Non-IPANEX/IPANEX	w/cm	$CaCl_2$	Type of Reinforcing
1	1	-1	-1	-1
2	1	-1	0	0
3	1	-1	1	1
4	1	0	-1	-1
5	1	0	0	0
6	1	0	1	1
7	1	1	-1	0
8	1	1	0	0
9	1	1	1	-1
10	-1	-1	-1	1
11	-1	-1	0	-1
12	-1	-1	1	0
13	-1	0	-1	0
14	-1	0	0	1
15	-1	0	1	-1
16	-1	1	-1	1
17	-1	1	0	-1
18	-1	1	1	0

Table 3.4 Explanation of Coding Used in DOE KISS

Variable		Coding
IPANEX	Non-IPANEX	-1
	IPANEX	1
w/cm	0.40	-1
	0.44	0
	0.48	+1
$CaCl_2$	0 lb/cy	-1
	2 lb/cy	0
	5 lb/cy	+1
Type of Reinforcing	Uncoated	-1
	Epoxy coated	0
	MMFX	+1

Six more combinations were added to the 18 combinations created by DOE KISS. These combinations were added to create direct comparison points. The 24 combinations used for ASTM G 109 are shown in Table 3.5.

Table 3.5 ASTM G 109 Specimen Combinations

IPANEX				Non-IPANEX			
w/cm = 0.40				w/cm = 0.40			
$CaCl_2$	Black	Epoxy	MMFX	$CaCl_2$	Black	Epoxy	MMFX
0				0	X	X	
2		X	*	2		*	X
5	X		X	5			
w/cm = 0.44				w/cm = 0.44			
$CaCl_2$	Black	Epoxy	MMFX	$CaCl_2$	Black	Epoxy	MMFX
0	X		X	0			
2				2	X	X	
5		X	*	5		*	X
w/cm = 0.48				w/cm = 0.48			
$CaCl_2$	Black	Epoxy	MMFX	$CaCl_2$	Black	Epoxy	MMFX
0		X	*	0		*	X
2	X		X	2			
5				5	X	X	
Note: “X” denotes 3 specimens from L18 design. “*” denotes 3 specimens added.							

Due to the different combinations an identification system was devised. The system consisted lettering a specimen NI for concrete not containing IPANEX, and a I for concrete with IPANEX. The w/cm was written next, followed by the amount of $CaCl_2$, in lb/cy, placed in the concrete. Lastly the specimen was denoted with either a B for uncoated or "black steel", a G for green epoxy coated steel, or M for MMFX steel. So for example a specimen labeled NI-0.44-2-G would denote non-IPANEX, w/cm of 0.44, with 2 lb/cy of $CaCl_2$ and a top bar of epoxy coated steel reinforcing.

3.4.2 Specimen Design

The specimens constructed for this test were concrete beams with dimensions of 4.5 in by 6 in by 11 in. Three 15 in long reinforcing bars were cast in each specimen. One #4 (0.5 in. diameter) reinforcing bar was placed at the top, which nominally served as the anode, supplying cat ions in the galvanic cell. Two #4 reinforcing bars were placed at the bottom to serve as the cathode. The bottom bars are black steel. The location of the reinforcement is shown in Figure 16 and 17. Plexiglass used to pond salt water, dams were placed on the top of the specimens. The dams were constructed of 1/16 in. thick plexiglass with dimension of 3 in. by 6 in. Completed specimens are shown in Figure 18.

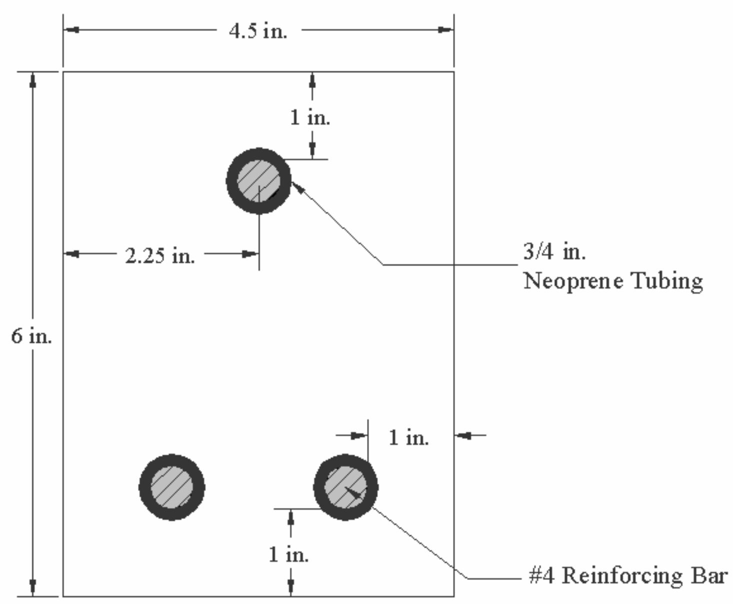


Figure 16: Location of Reinforcement for ASTM G 109 (front view)

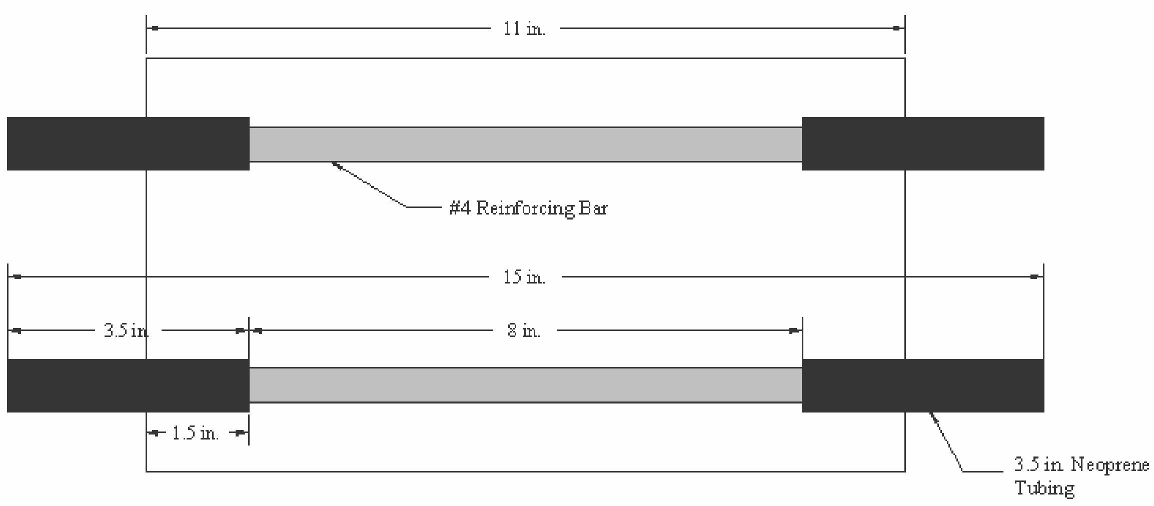


Figure 17: Location of Reinforcement for ASTM G 109 (section view)

Figure 18: Completed G 109 Specimens

3.4.3 Concrete Proportioning

Three concrete mixtures were used to cast the specimens. All of the concrete mixtures used Type I cement from Lafarge Building Materials (Tulsa, Oklahoma). The coarse aggregate used was # 57 crushed limestone (1 ½ in. nominal) supplied by Dolese Bros. Co. (Oklahoma City, Oklahoma). Dolese also provided the calcium chloride ($CaCl_2$) in a 32% concentration. The sand used had a fineness modulus of 2.59 and was from an unknown origin. All concrete mixtures contained Class C fly ash provided by Mineral Solutions (Springfield, Missouri) from the OG&E Sooner Power plant near Red Rock, Oklahoma. The concrete also used the air entrainment admixture MB AE 90 supplied by Master Builders Inc. Some concrete also contained a permeability reducing admixture, IPANEX provided by IPA Systems, Inc. (Philadelphia, Pennsylvania).

The mix proportions of the three concrete mixtures are shown below in Table 3.6. The mix proportions for the Kay County Bridge decks are shown in Table 3.7 for comparison.

Table 3.6 Concrete Mixture Proportions

Quantities per Cubic Yard	**Concrete**		
	w/cm = 0.40	w/cm = 0.44	w/cm =0.48
Cement (lbs)	559	506	464
Water (lbs)	275	275	275
Fly Ash (lbs)	133	119	109
Rock (lbs)	1710	1710	1710
Sand (lbs)	1272	1262	1306
Air Entrainer (fl oz./cwt)	0.9	0.9	0.9
IPANEX (fl oz./cwt)	13.8	13.8	13.8
$CaCl_2$ (lbs)	0, 2, or 5	0, 2, or 5	0, 2, or 5

Table 3.7 Concrete Mixture Proportions for Kay County Bridge Decks

Quantities per Cubic Yard	
Cement (lbs)	559
Water (lbs)	275
Rock (lbs)	1710
Sand (lbs)	1272
Fly Ash (lbs)	133
Air Entrainer (fl oz./cwt)	0.9
IPANEX (fl oz./cwt)	13.8

3.4.4 Fabrication of Specimens

All reinforcement was cut to length on a band saw, and except for the epoxy coated bars were power wire brushed to remove all rust and mill scale. Epoxy coated reinforcing bars were provided by Hearon Steel (Muskogee, Oklahoma). MMFX reinforcing bars were provided by MMFX Steel Corporation (Charlotte, North Carolina). The reinforcing was drilled on a lathe, and the threads were tapped using a drill press. Both ends of all reinforcing bars were wrapped with electroplaters tape for a length of 3.5 in. A 3.5 in. piece of neoprene tubing (0.5 in. ID, 0.75 in. OD) was then placed on each end. A stainless steel screw with a nut was threaded into on end of the bar and then two part waterproof epoxy was placed on the very end of each bar, covering both the steel and the tubing.

The bars were then placed into the assembled formwork so that an equal length was protruding from both ends as shown in Figure 19. For the G 109 test the top reinforcing bar is the anode, and the bottom two reinforcing bars are the cathode. Therefore the top bar was black, epoxy coated, or MMFX steel, depending upon the specimen. The bottom bars were both black steel for all specimens.

Figure 19: Completed Reinforcing Bars in Formwork

Concrete for the specimens was mixed in accordance with ASTM C 192/C 192M-00. All of the batches were mixed in the Kercher Industries 30-DH concrete pan mixer in the Civil Engineering Annex Laboratories.

The temperature of the fresh concrete was measured in accordance to ASTM C 1064/C 1064M-99. The slump of the fresh concrete was measured in accordance to ASTM C143/C 143M-98. The unit weight of the fresh concrete was measured in accordance to ASTM C138-92. The air content of the fresh concrete was measured in accordance to ASTM C 231-97. Twelve 4 x 8 in. cylinders were also cast in accordance with C 192/C 192M-00 to test compressive strength. Mix designs and fresh properties of each batch can be found in Appendix A.

The capacity of the mixer only allows approximately 2.5 ft^3 of concrete to be mixed properly. Therefore, six specimens were cast at one time. ASTM G 109 requires three replicates to be made, so three specimens were cast with one type of steel and the other three were cast with a different type of steel. The concrete for each specimen was placed in two lifts. A vibrating table was used consolidate the concrete for each lift as shown in Figure 20. The top of the specimens were finished with a wooden float. The specimens were placed in the curing chamber for approximately 24 hours. They were then taken out of the chamber, the forms stripped, and placed back in the curing chamber. The specimens were cured for 28 days in the curing room in accordance to ASTM C 192/C 192M-00. The curing chamber maintained a temperature of $73 \pm 3°$ F and a relative humidity (RH) of 95%. A total of 72 specimens were made.

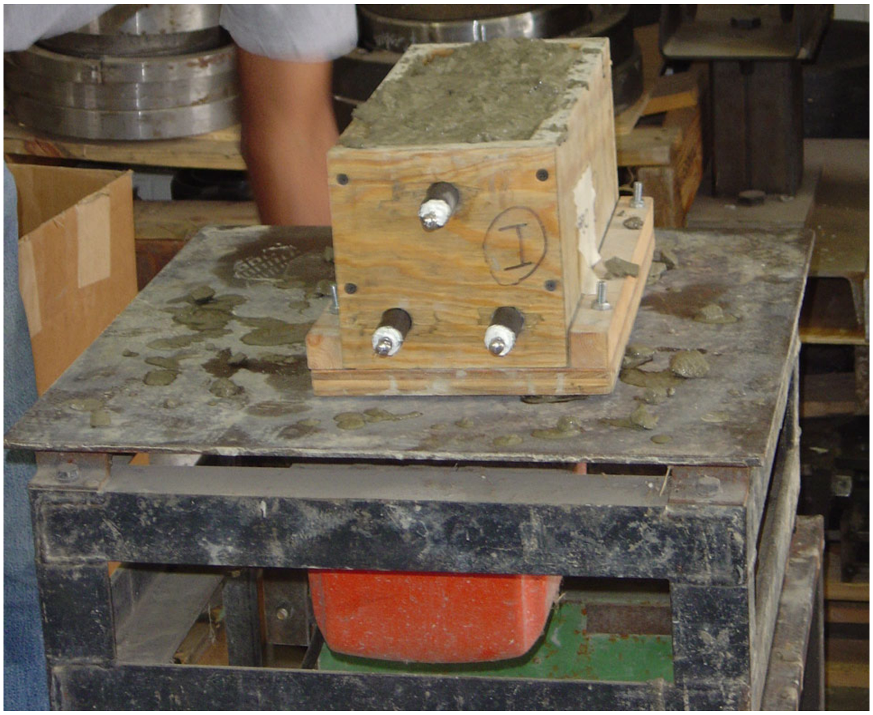


Figure 20: Consolidation of Concrete

When the specimens were removed from the curing room they were cured 14 more days in the Concrete Lab in the Engineering Annex at 50% RH. The top surface of the concrete was hand wire brushed. Plexiglass dams were then attached to the top of the specimens with silicon caulking. The specimens were then coated with Epoxy Concrete Sealer #12560 made by Devcon. The epoxy was applied to the four vertical sides and the top, except on the inside of the plexiglass dams. Attention was focused on making a waterproof seal between the dams and the concrete.

Wires were attached to each of the screws on the end of each reinforcing bars, and the bottom two wires were connected together to form one wire. A 100 ohm resister was soldered between the top and bottom wires. The specimens began to be tested 14 days after the epoxy coating was applied. Completed specimens are shown in Figure 21.

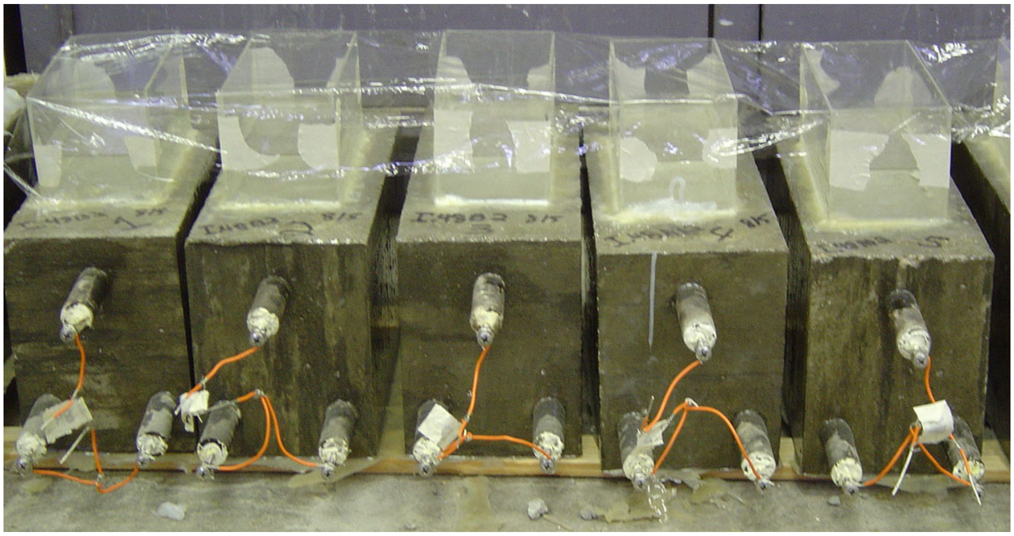


Figure 21: Completed Specimens Ponded with 3% NaCl Solution

3.4.5 Testing Procedure

In conformance with ASTM G 109 the specimens were ponded with 400 ml of 3% (by weight) NaCl solution for two weeks. At the end of the two weeks the solution was removed. The NaCl solution was removed by vacuuming it off. The specimens were allowed to dry two weeks. The specimens were ponded again, and the whole process was repeated.

Voltage readings were measured across the resistors with a multimeter. Because the voltage is measured across a known resistance, the macro cell current can be calculated using Ohm's Law. The voltages were divided by the resistance values of the resistor in order to calculate the macro cell current.

The corrosion potential of each specimen was also measured. A Corning 476046 reference electrode was used to measure the potentials. Corrosion potentials were only measured when the specimens were ponded. There must be a path of moisture between the electrode and the concrete in order for potentials to be measured. Measurement of corrosion potential is shown in Figure 22.

Figure 22: Measurement of Corrosion Potential

Initially, macrocell current and corrosion potentials were only measured once a month, at the end of ponding. Three months after testing began both measurements were made every week for the respective specimen. This included one measurement when there was no NaCl solution present, so corrosion potentials were not able to be measured.

3.5 Tension Tests of MMFX Reinforcement and Grade 60 Reinforcing Bars

In order to obtain material properties of the two types of steel used, tension tests were performed on both MMFX and Grade 60 reinforcing bars. Two different test setups were used to measure the material properties.

3.5.1 Specimen Design

#3 (0.375 in.) reinforcing bars were used for all testing. Three test specimens were prepared for each type of steel for both test setups. The reinforcing bars were cut into two foot lengths. One inch of threads were dyed onto each end of the bars. The middle four inches of six bars were machined to a diameter of 0.250 in., shown in Figure 23. These bars were used for the extensometer setup. The middle four inches of six other bars were machined to a diameter of 0.300 in. These bars were used for the LVDT setup.

3.5.2 Variables Measured

The tension test measured two variables. The load applied by the hydraulic cylinder, and the extension of the reinforcing bar under load were recorded. Yield stress, yield strain, ultimate strength, elastic modulus, and percent elongation were calculated from the recorded data. A stress strain graph was also developed from this data.

3.5.3 Test Setup Using Extensometer

The apparatus used for this test setup consisted of an extensometer attached to the reinforcing bar, and an upper and lower frame attached to a MTS 810 Material Testing System. The reinforcing bar was machined to a diameter of 0.250 in.

A MTS Model 632.25B-20 extensometer was used for this setup. This extensometer is shown in Figure 23. The extensometer was placed approximately in the middle of the 4 in. machined section of the reinforcing bar. The gauge length of the extensometer is 2 in. Unless the specimen yielded in the gauge length, the extensometer only captured the extension of the steel until it yielded.

Figure 23: Attachment of Extensometer

A steel block with dimensions of 2 in. by 2 in. by 1 in. was screwed onto each end of the test specimen. These blocks held the specimen between the upper and lower frames of the MTS machine. These blocks are visible at each end of the specimen in Figure 24.

The lower frame consisted of two 1.25 in. thick plates and two C8 x 11.5 channels. The lower plate had a 1 in. hole to attach the loading frame to the MTS actuator, and the upper plate had a 9/16 in. slot to place the specimens in the frame.

The upper frame consisted of two 1.5 in. thick plates and two C8 x 11.5 channels. The upper plate had a 1 in. hole to attach the loading frame to the MTS crosshead, and the lower plate had a 9/16 in. slot to place the specimens in the frame. These frames are shown in Figure 24 attached to the MTS machine.

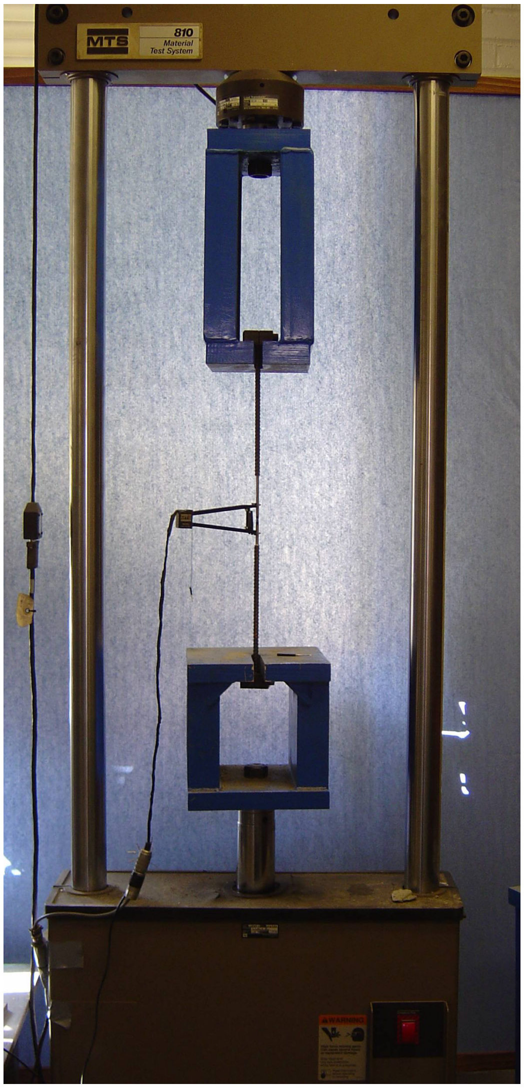


Figure 24: Test Setup Using Extensometer

The hydraulic cylinder in the MTS machine applied load to the specimen at a constant displacement. The displacement of the cylinder was set to 0.25 in. per minute. The force applied to the specimen was measured by the load cell of the MTS machine. The extensometer measured the extension of the bar. The desktop computer connected to the MTS machine recorded extension of the bar as measured by the extensometer, and the load applied to the bar. The test was run until the specimen fractured. Three tests of both types of reinforcement were conducted

. Elastic modulus, yield stress, strain at yield, and ultimate stress were calculated from the data obtained. Stress was calculated by dividing the load by the reduced cross sectional area. Strain was calculated by dividing the extension of the bar by the gauge length of the extensometer, 2in. Stress strain graphs were produced from the calculated stresses and strains. The elastic modulus was calculated by finding the slope on the stress strain graphs from 10 – 60 ksi.

3.5.4 Test Setup Using Linear Variable Differential Transformer

The apparatus used for this test setup consisted of a linear variable differential transformer (LVDT) attached to the reinforcing bar and, an upper and lower frame attached to a MTS 810 Material Testing System. The reinforcing bar was machined to a diameter of 0.300 in. The upper and lower frames were the same used in the test setup using the extensometer.

A RDP DCT 1000A LVDT was used for the testing. An 8 in. gauge length was used. The LVDT was attached to the reinforcing bar at two points. The two points of attachment were 2 in. above and below the 4 in. machined section of the reinforcing bar. The LVDT attached to a reinforcing bar is shown in Figure 25.

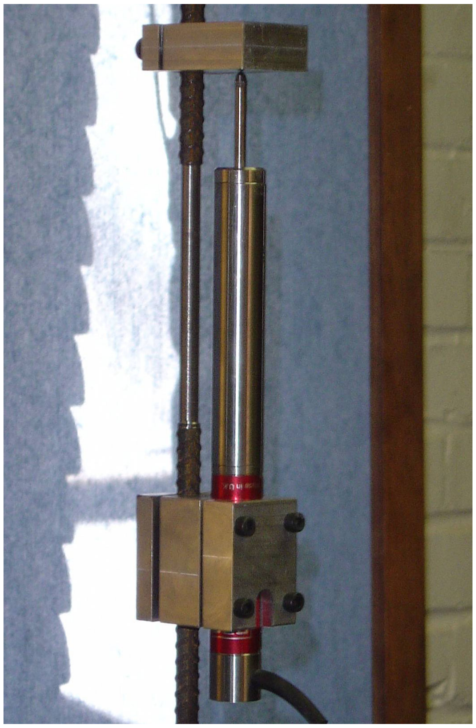


Figure 25: Attachment of LVDT

The hydraulic cylinder in the MTS machine applied load to the specimen at a constant displacement. The displacement of the cylinder was set to 0.06 in. per minute. The force applied to the specimen was measured by the load cell of the MTS machine. The extensometer measured the extension of the bar. The desktop computer connected to the MTS machine recorded extension of the bar as measured by the extensometer, and the load applied to the bar. The test was run until the specimen fractured. Three tests of both types of reinforcement were conducted.

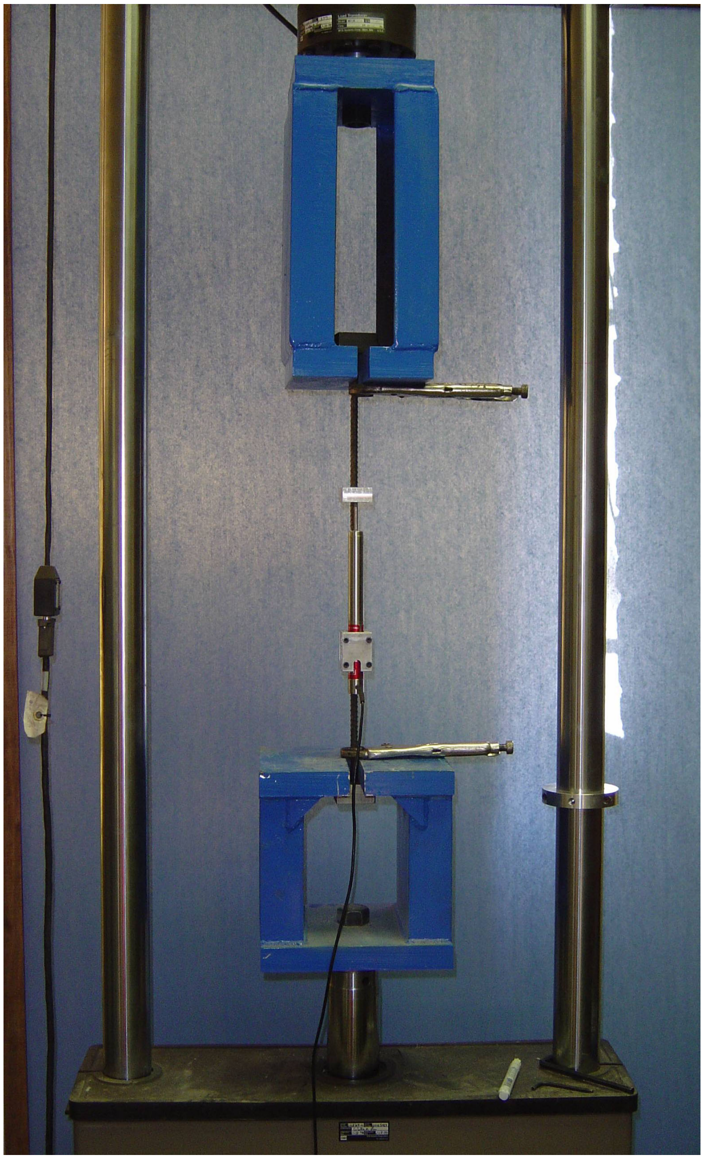
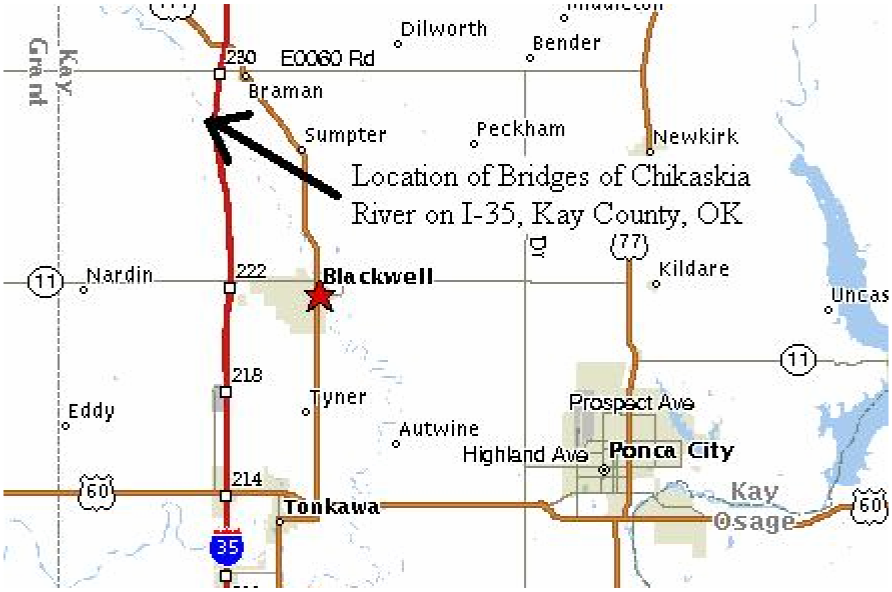


Figure 26: Test Setup Using LVDT

Ultimate stress and percent elongation were calculated from the data obtained. Yield stress was calculated for black steel because a definite yield point was evident. Stress was calculated by dividing the load by the reduced cross sectional area. Percent elongation was calculated by dividing the extension of the bar at failure by the length of the reduced cross section, 4 in. Stress strain graphs were produced from the calculated stresses and strains.

3.6 Coring of Bridge Decks

Cores were taken from bridge decks in order to measure hardened properties of the concrete. These properties were compressive strength and chloride permeability. The cores were taken from a pair of bridges located on I-35 in Kay County, Oklahoma over the Chikaskia River.



Location of Bridges of Chikaskia River on I-35, Kay County, OK

Figure 27: Location of Bridges over Chikaskia River on I-35, Kay County, OK

Pairs of cores were taken at relatively equal spacing along the third span. The 4 or 6 in the core designation identifies if the core was taken four feet or six feet from the curb. Once removed from the deck, the cores were wrapped in plastic and stored in the curing room of the concrete laboratory in the Engineering Annex until needed for testing. The approximate locations of the corings are shown in Figures 28 and 29. The northbound bridge deck concrete contained IPANEX, and the southbound bridge deck concrete did not.

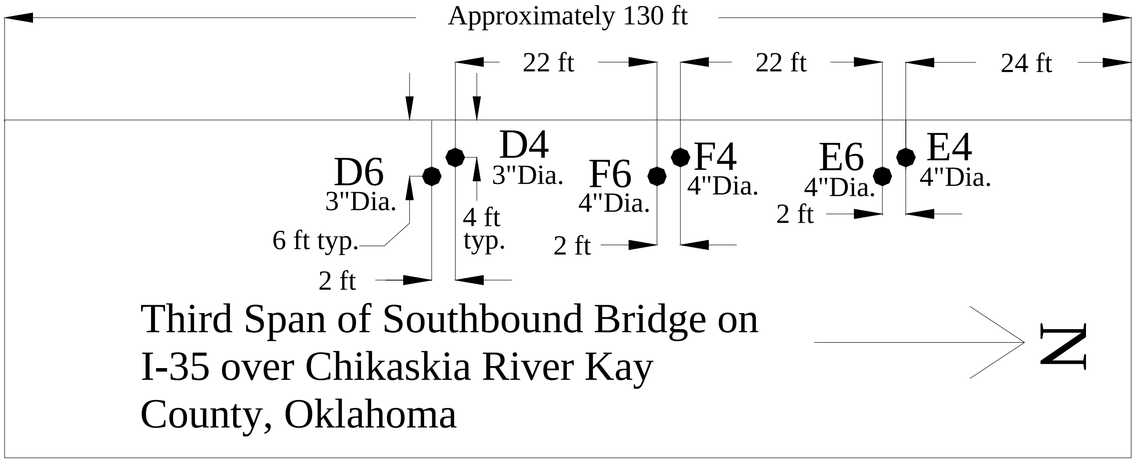


Figure 28: Location of Corings on Kay County Bridges

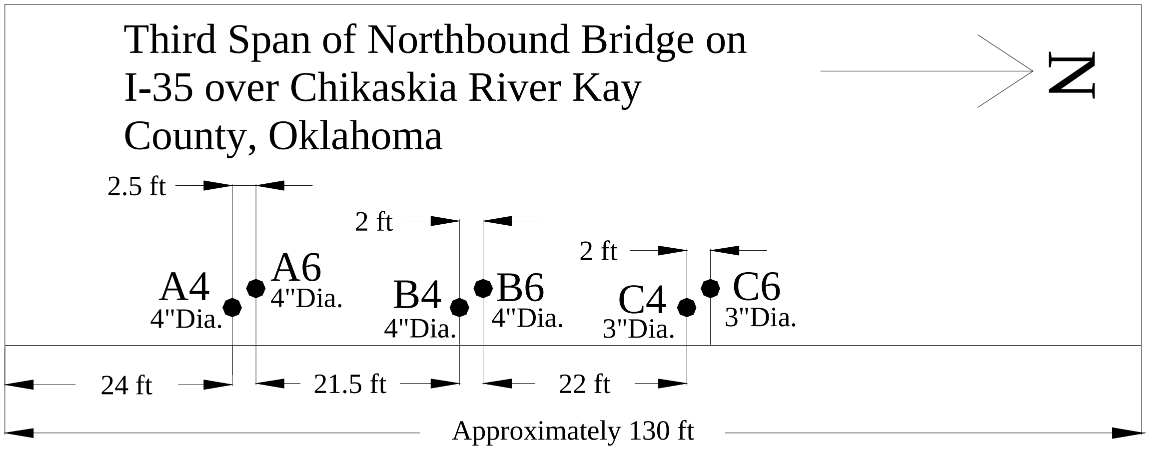


Figure 29: Location of Corings on Kay County Bridges

3.7 ASTM C 39/C 39M-01 Compression Testing of Cores

A three inch coring bit was used to take cores from the bridge decks for compression testing. This size bit was used in order to obtain a core with the minimum length to diameter ratio of 1.0 that ASTM C 39 specifies. Cores C4, C6, D4, and D6 were tested for compressive strength.

The bottom of each core was sawn with a water cooled diamond saw blade to obtain a perpendicular face for testing. The diameter and length of each core was measured. A correction factor was calculated if the length to diameter ratio was less than 1.8. The description of each core is shown in Table 3.8.

Once the cores were sawn they were tested for compressive strength in conformance with ASTM C 39, and the ultimate strengths were recorded.

Figure 30: Core C6 Before and After Sawing End

Table 3.8 Dimensions of Cores Tested For Compressive Strength

Core	Diameter (in.)	Original Length (in.)	Sawed Length (in.)	Length to Diameter Ratio	Correction Factor	Notes:
C4	2.75	7.25	7.22	2.64	1	Steel 2.5" from top
C6	2.75	4.50	4.35	1.59	0.97	Steel 2.5" from top
D4	2.75	5.75	5.70	2.08	1	Steel 2.5" from top
D6	2.75	6.25	6.05	2.20	1	Steel 2.5" from top

3.8 ASTM C1202-97 Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

This test measures the ability of chloride ions to penetrate concrete by applying a voltage of 60 V DC across the ends of a 2 in. slice of a concrete cylinder for 6 hours. One end of the slice is immersed in a 0.3 N sodium hydroxide solution and the other end is immersed in a 3% (by mass) sodium chloride solution. The total charge passed through the slice in 6 hours measures the permeability of the concrete to chloride penetration. A table rating the chloride penetrability based on the amount of charge passed is shown in Table 3.9.

Table 3.9 Chloride Ion Penetrability Based on Charge Passed (Table 1, ASTM C 1202 -97)

Charge Passed (coulombs)	Chloride Ion Penetrability
> 4000	High
2000 – 4000	Moderate
1000 - 2000	Low
100 – 1000	Very Low
< 100	Negligible

A 4 in. coring bit was used to take four cores from each bridge deck for the C 1202 test. This produced specimens with an actual diameter of 3.75 in. which is the desired diameter for C 1202. Cores A4, A6, B4, B6, E4, E6, F4, and F6 were tested in accordance with the C 1202 test method. Four specimens were also tested from a batch of concrete made in the Engineering Annex. This batch was denoted as I-0.40-0, and is the same mix design as the northbound bridge deck concrete in the Kay County bridges. The mix design, fresh properties, and 1, 7, and 28 day strengths of I-0.40-0 can be found in Appendix A.

Table 3.10 Specimens Used In ASTM C 1202 Tests

Concrete	Specimens	w/cm	IPANEX	Age (days)
Northbound bridge deck	Four 3.75 in. diameter cores	0.40	Yes	400
Lab. Batch of Northbound (I-0.40-0)	Four 4 x 8 in. cylinders	0.40	Yes	31
Southbound Bridge Deck	Four 3.75 in. diameter cores	0.40	No	715
Lab. Batch of Southbound (NI-0.40-0)	Four 4 x 8 in. cylinders	0.40	No	126

3.8.1 Testing Procedure

In conformance with ASTM C 1202, 2 in. slices were cut from the top of each core or cylinder. These slices were de-aerated in the vacuum saturation apparatus for 3 hours at a pressure of 133 Pascals. The vacuum saturation apparatus is shown in Figure 32. Sufficient de-aerated water was added into the vacuum saturation apparatus to cover the slices completely. The vacuum was maintained for an additional hour. Air was allowed to re-enter the vacuum apparatus, and the slices were soaked in the de-aerated water for 18 ± 2 hours. The conditioned specimens were placed in an applied voltage cell connected to the constant voltage power supply and data readout apparatus. A constant voltage of 60 V DC was applied to the voltage cell for six hours. The current passed through the sample over 6 hours is recorded. This current is integrated over time to calculate the total charge passed through the specimen in coulombs. The applied voltage cell connected to the constant voltage power supply and data readout apparatus is shown in Figure 33.

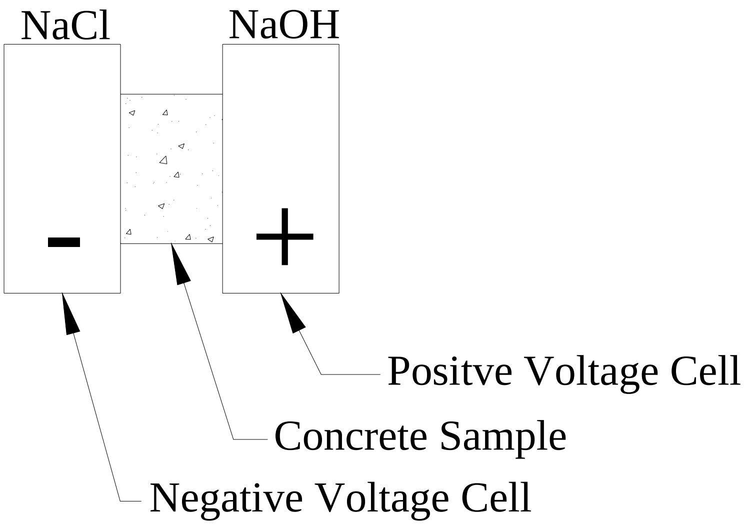


Figure 31: Schematic of Applied Voltage Cell for ASTM C 1202

Figure 32: Vacuum Saturation Apparatus for ASTM C 1202

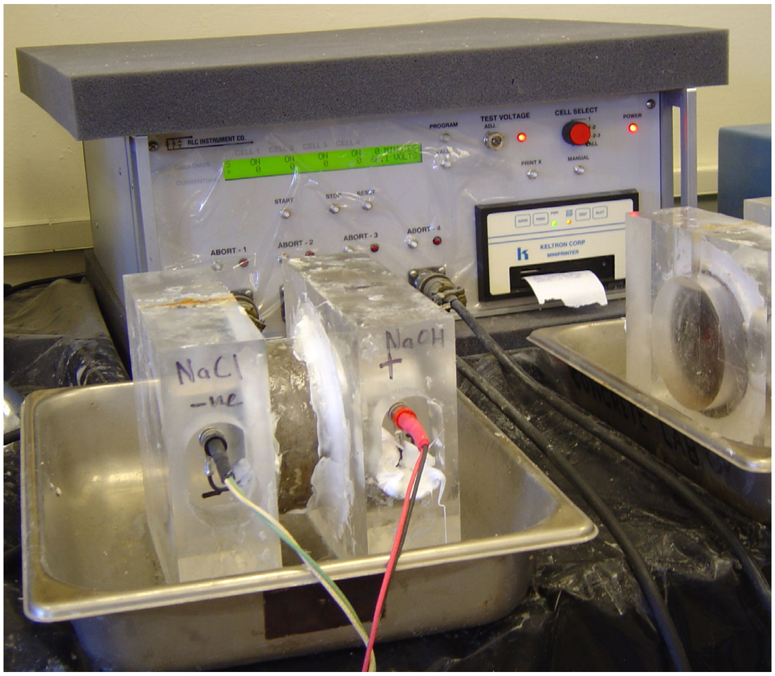


Figure 33: Applied Voltage Cell with Constant Voltage Power Supply and Data Readout Apparatus

3.9 ASTM C 469-94 "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression"

This test measures the chord modulus of elasticity of concrete cylinders or concrete cores in compression. This test method measures longitudinal strains and stresses. Because this test method determines a chord modulus, only two data points are necessary to calculate the modulus. The applied load and deformation are recorded at the point where the longitudinal strain is equal to 50 millionths and when the applied load is equal to 40% of the ultimate load. The test setup is shown below in Figure 34.

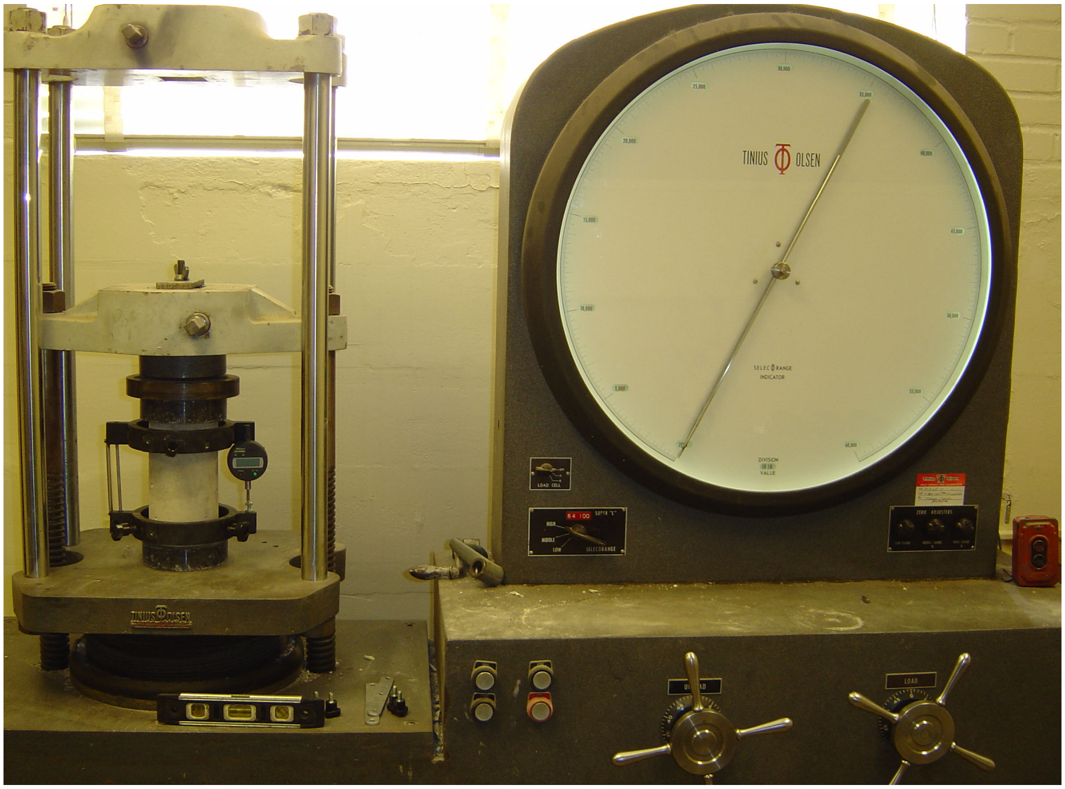


Figure 34: Test Setup for ASTM C 469-94 Test Method

Two groups of field cast cylinders were tested in accordance with test method C 469. The cylinders were cast during two separate bridge deck placements of the northbound bridge over the Chikasia River on I-35 in Kay County, Oklahoma. The first group of cylinders was cast on January 7, 2003 and the second group of cylinders was cast on January 20, 2003. Each group consisted of four cylinders with the admixture IPANEX.

Table 3.11 Specimens Used in ASTM C 469 Tests

Designation	Concrete	IPANEX	Age (days)
G-1	Field cast 4x8 in. cylinders from northbound bridge deck	yes	408
G-2	Field cast 4x8 in. cylinders from northbound bridge deck	yes	421

One cylinder from each group was tested for compressive strength in conformance with ASTM C 39 to obtain a compressive strength. The cylinders were then tested in conformance with test method C 469. Deformation was recorded at every 1000 lb of load. Test method C 469 requires at least three loadings up to 40% of the ultimate load. The first load is for seating of the gauges, and the calculation of modulus is based upon the average of the two subsequent loadings.

4. TEST RESULTS

4.1 Results of ASTM G 109-99

4.1.1 Total Corrosion of Specimens

There were 72 specimens made for the G 109 test. There were three specimens made for each of the 24 combinations.

The total corrosion of each specimen was calculated in conformance with ASTM G 109. The total corrosion is the integration of the macrocell current over time. Expressed in equation form this is:

$$TC_j = TC_{j-1} + \left[(t_j - t_{j-1})(i_j + i_{j-1})/2\right]$$

Where TC is the total corrosion in coulombs, t_j is the time in seconds when the macrocell current was measured, and i_j is the macrocell current in amps at time, t_j. The total corrosion of the specimens as of April 2, 2004 is shown in Table 4.1.

Table 4.1 Total Corrosion of Specimens in Test Method G 109

Number	Combination	Total Corrosion (Coulombs)		
		Specimen 1	Specimen 2	Specimen 3
1	NI-0.40-0-B	0.00	0.00	0.00
2	NI-0.40-0-G	0.00	0.00	0.00
3	NI-0.40-2-G	0.00	0.00	0.00
4	NI-0.40-2-M	0.00	3.13	16.26
5	NI-0.44-2-B	1.73	9.57	7.17
6	NI-0.44-2-G	0.00	0.00	0.00
7	NI-0.44-5-G	0.00	0.00	0.00
8	NI-0.44-5-M	26.30	1.72	1.76
9	NI-0.48-0-G	0.00	0.00	0.00
10	NI-0.48-0-M	1.78	1.71	1.71
11	NI-0.48-5-B	101.09	29.26	193.26
12	NI-0.48-5-G	0.00	28.36	0.58
13	I-0.40-2-G	0.00	0.00	0.00
14	I-0.40-2-M	0.00	0.00	0.00
15	I-0.40-5-B	28.54	35.28	31.80
16	I-0.40-5-M	0.00	5.68	1.99
17	I-0.44-0-B	3.09	2.55	2.73
18	I-0.44-0-M	8.31	6.18	8.25
19	I-0.44-5-G	0.00	0.00	0.00
20	I-0.44-5-M	0.00	0.00	1.73
21	I-0.48-0-G	1.68	0.00	0.00
22	I-0.48-0-M	0.00	4.02	0.00
23	I-0.48-2-B	264.30	20.29	197.68
24	I-0.48-2-M	1.98	16.13	0.00

4.1.2 Average Macrocell Current and Average Corrosion Potential

The following graphs are the average macrocell current versus time and the average corrosion potential versus time for each combination made for ASTM G 109. The full record of each reading for each specimen can be found in Appendix B.

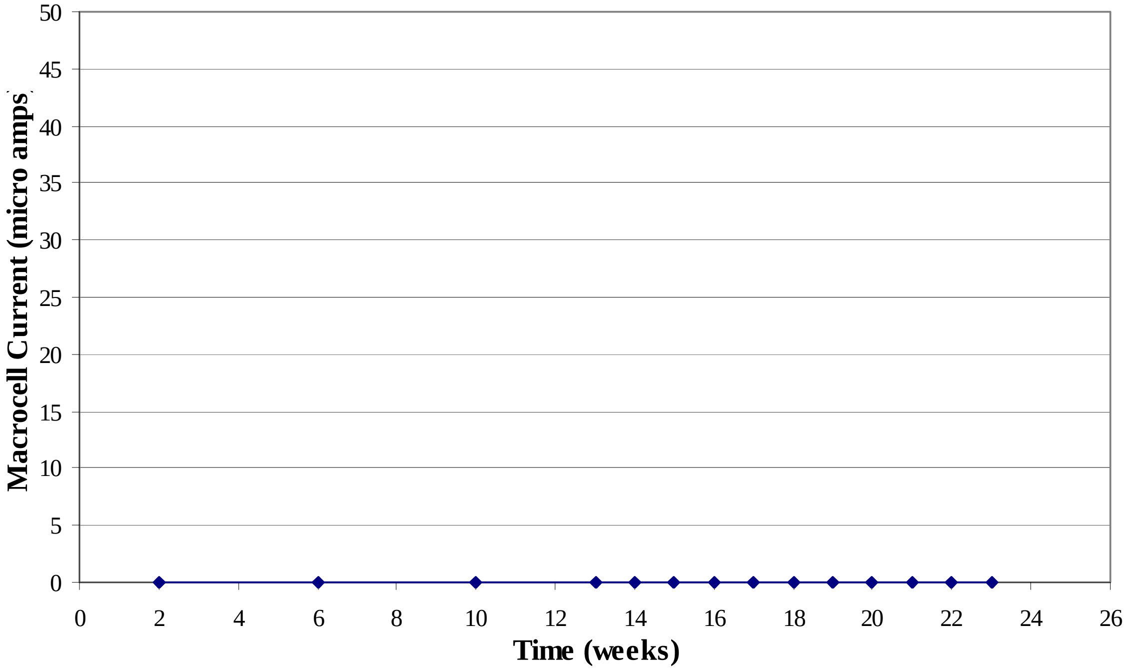


Figure 35: I-0.40-2-G Average Macrocell Current vs. Time

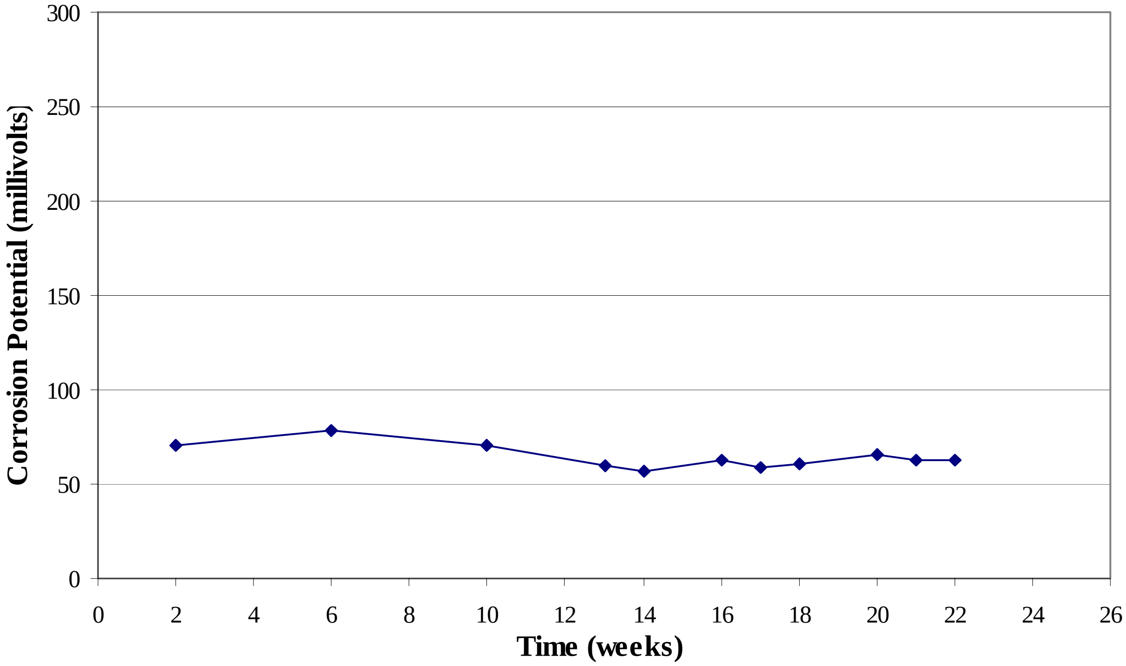


Figure 36: I-0.40-2-G Average Corrosion Potential vs. Time

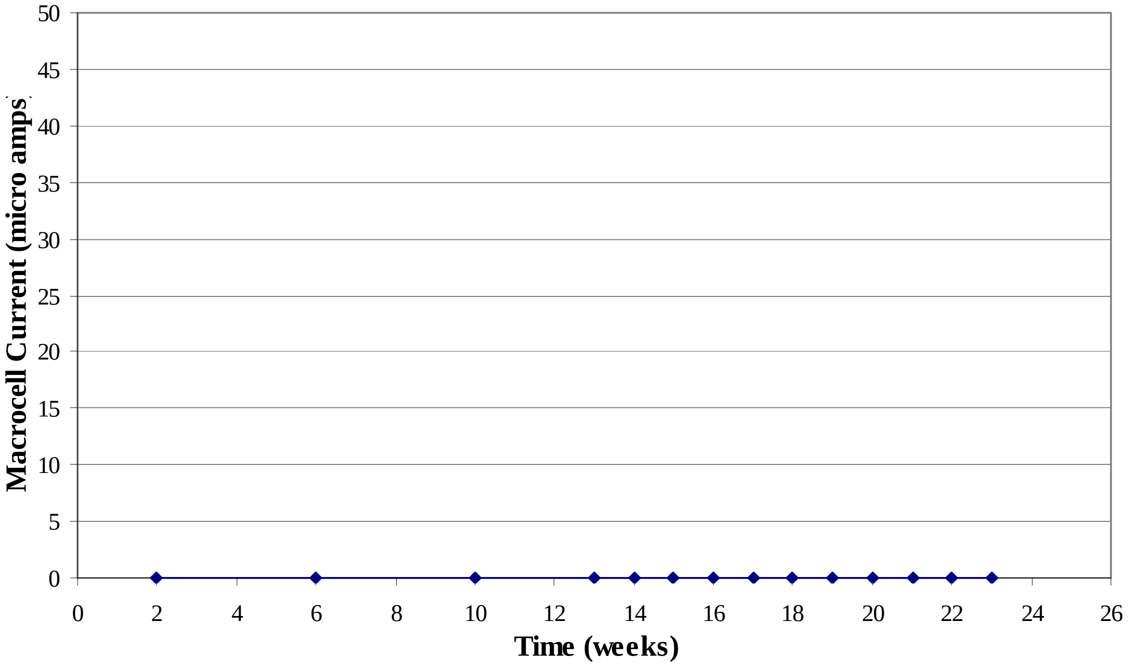


Figure 37: I-0.40-2-M Average Macrocell Current vs. Time

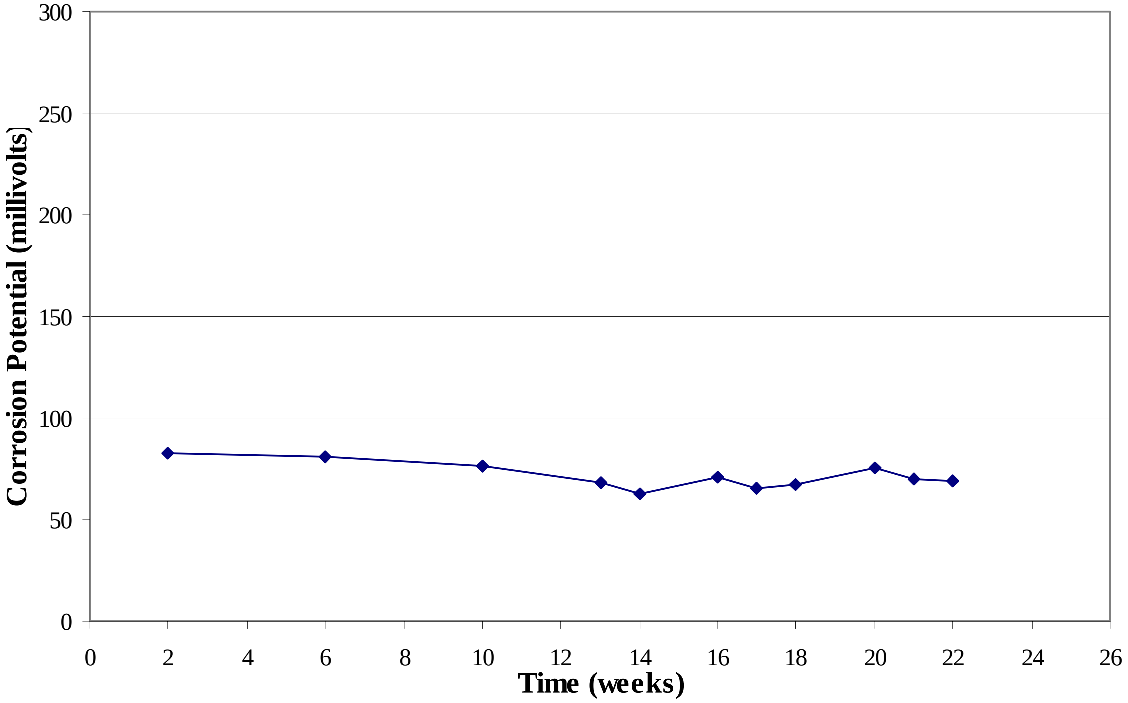


Figure 38: I-0.40-2-M Average Corrosion Potential vs. Time

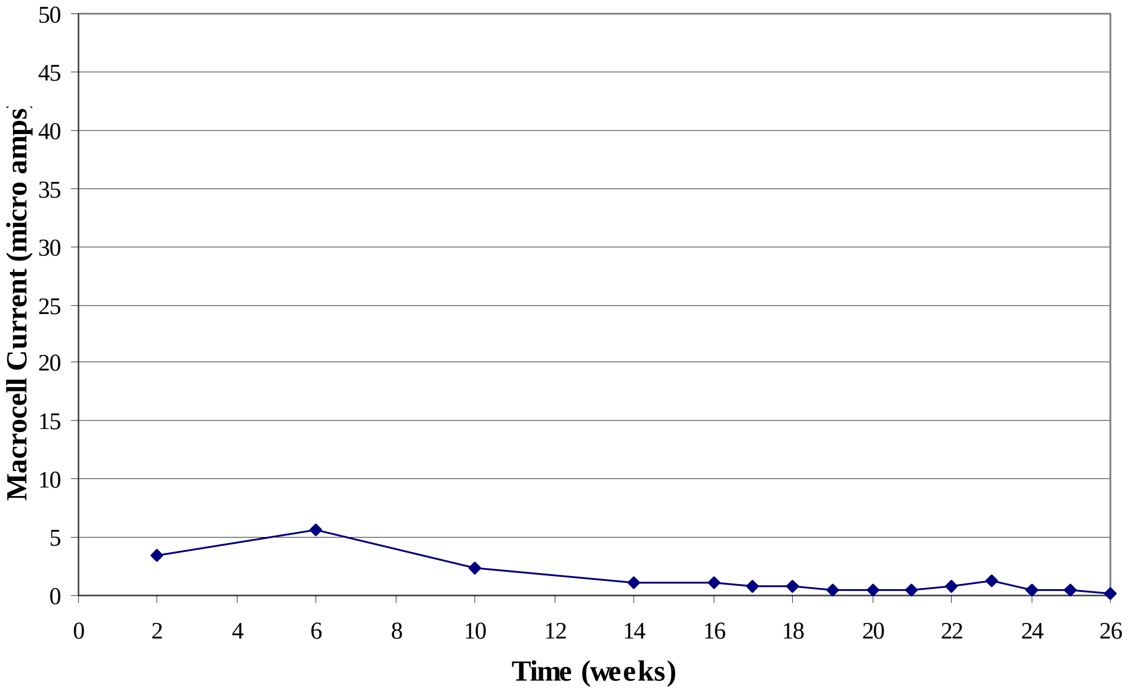


Figure 39: I-0.40-5-B Average Macrocell Current vs. Time

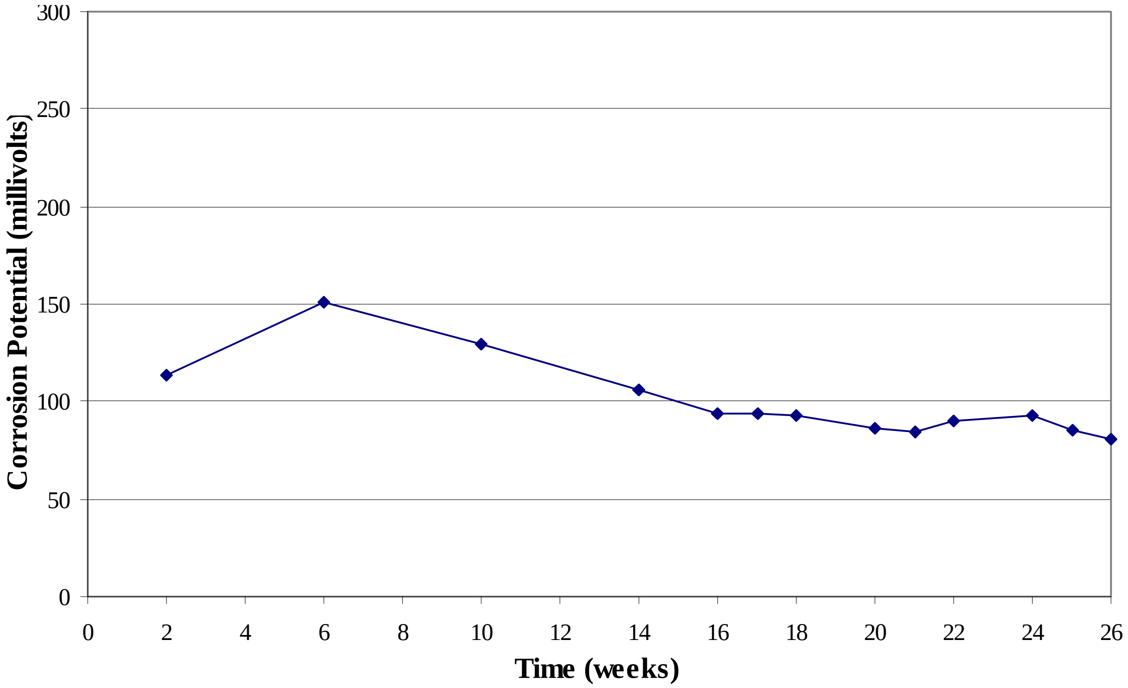


Figure 40: I-0.40-5-B Average Corrosion Potential vs. Time

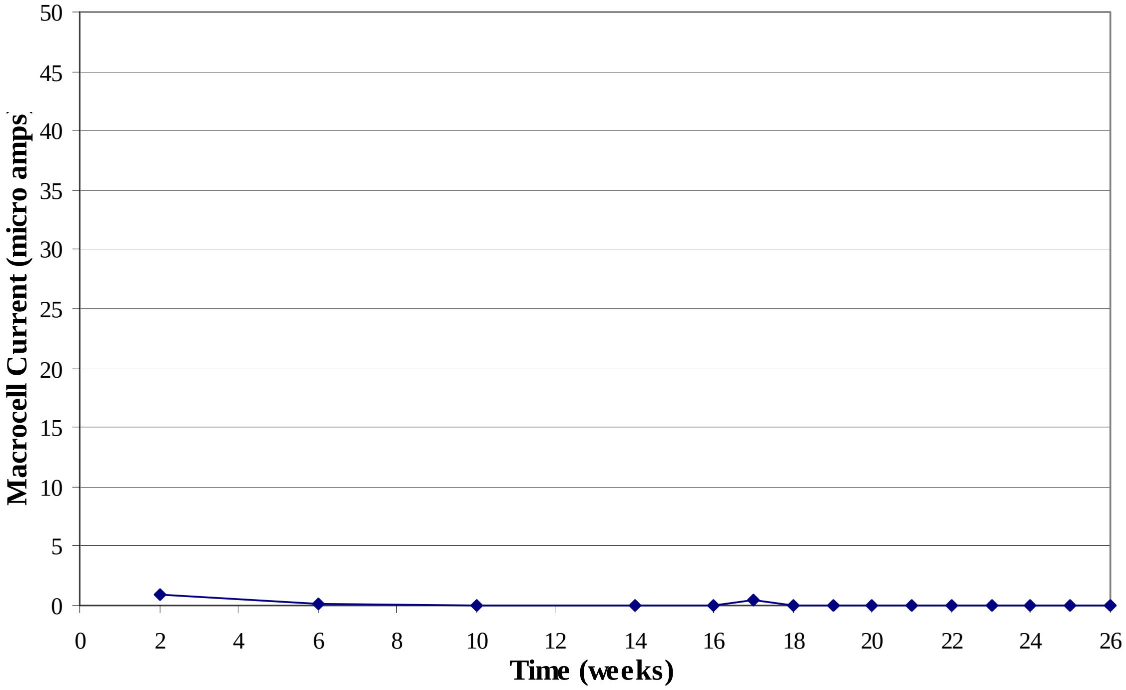


Figure 41: I-0.40-5-M Average Macrocell Current vs. Time

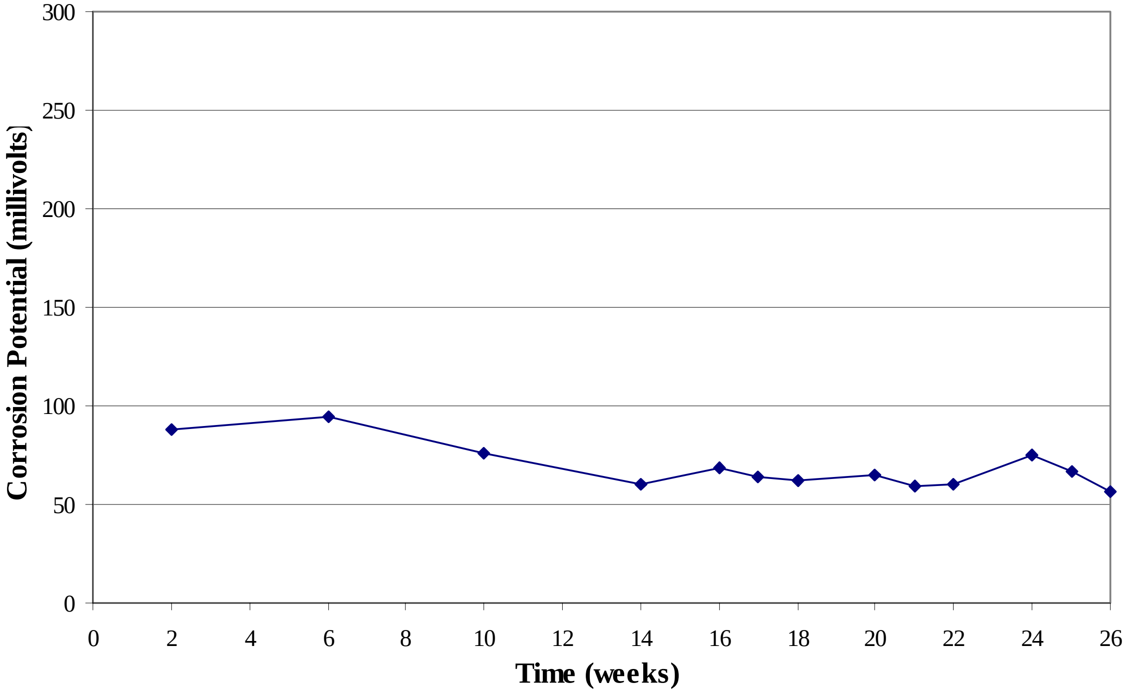


Figure 42: I-0.40-5-M Average Corrosion Potential vs. Time

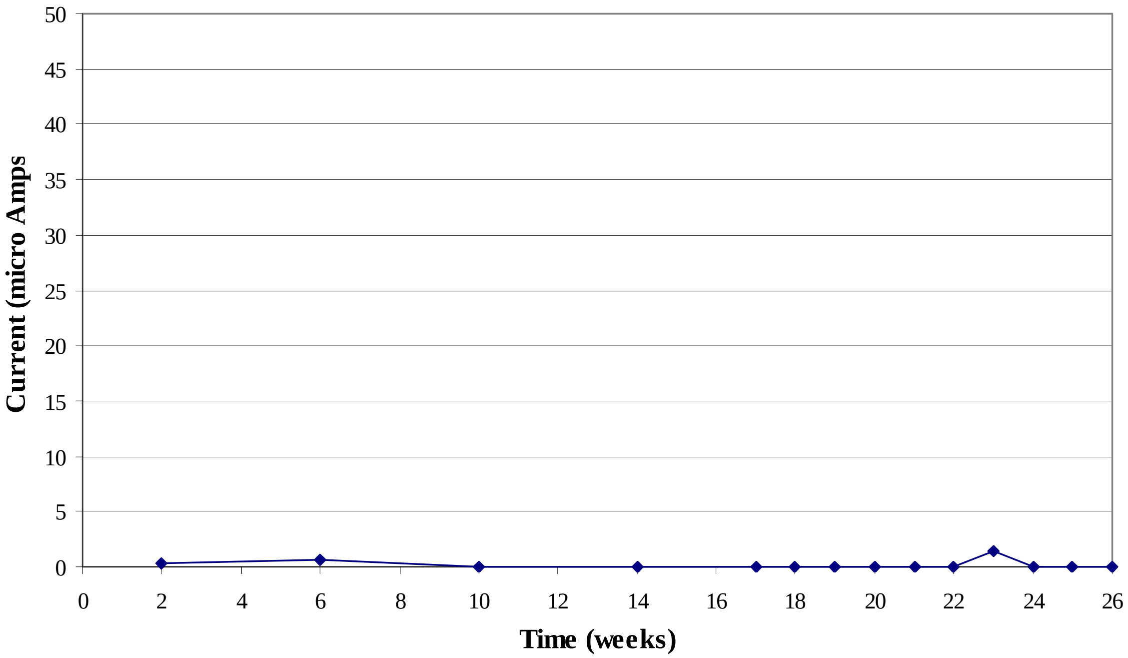


Figure 43: I-0.44-0-B Average Macrocell Current vs. Time

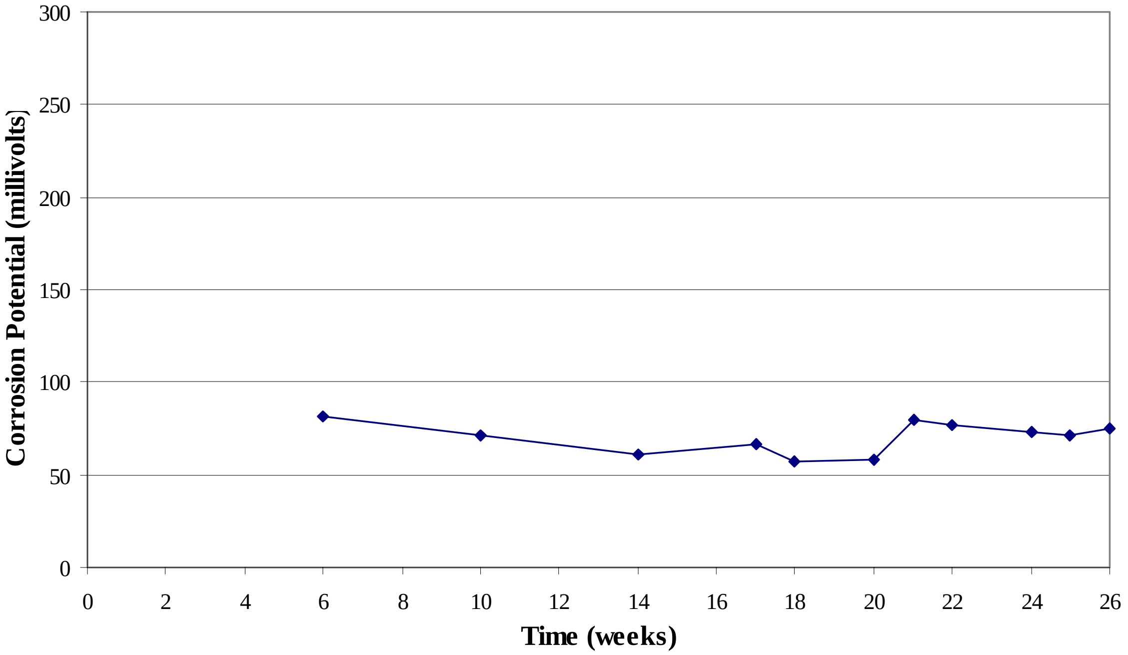


Figure 44: I-0.44-0-B Average Corrosion Potential vs. Time

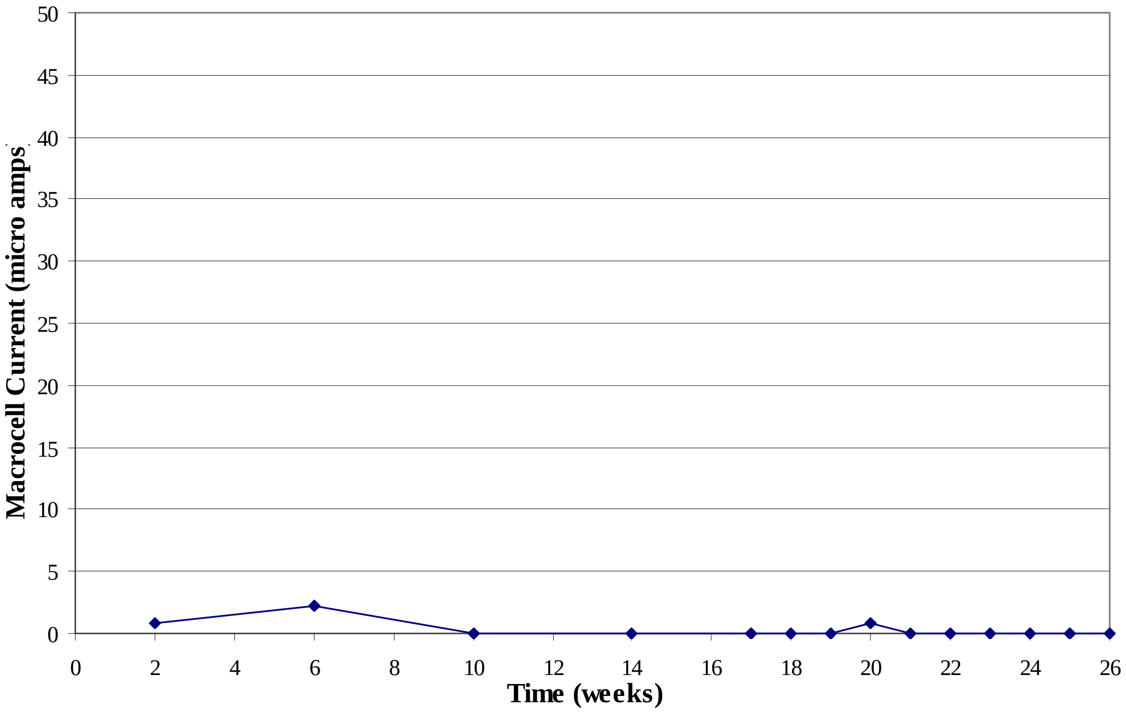


Figure 45: I-0.44-0-M Average Macrocell Current vs. Time

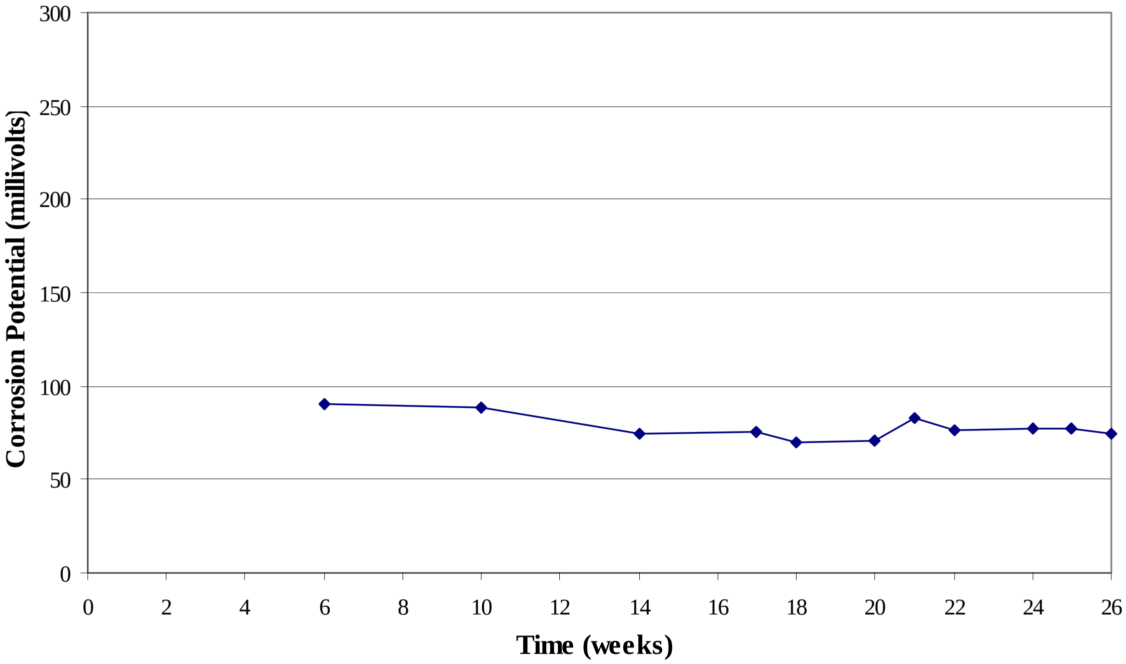


Figure 46: I-0.44-0-M Average Corrosion Potential vs. Time

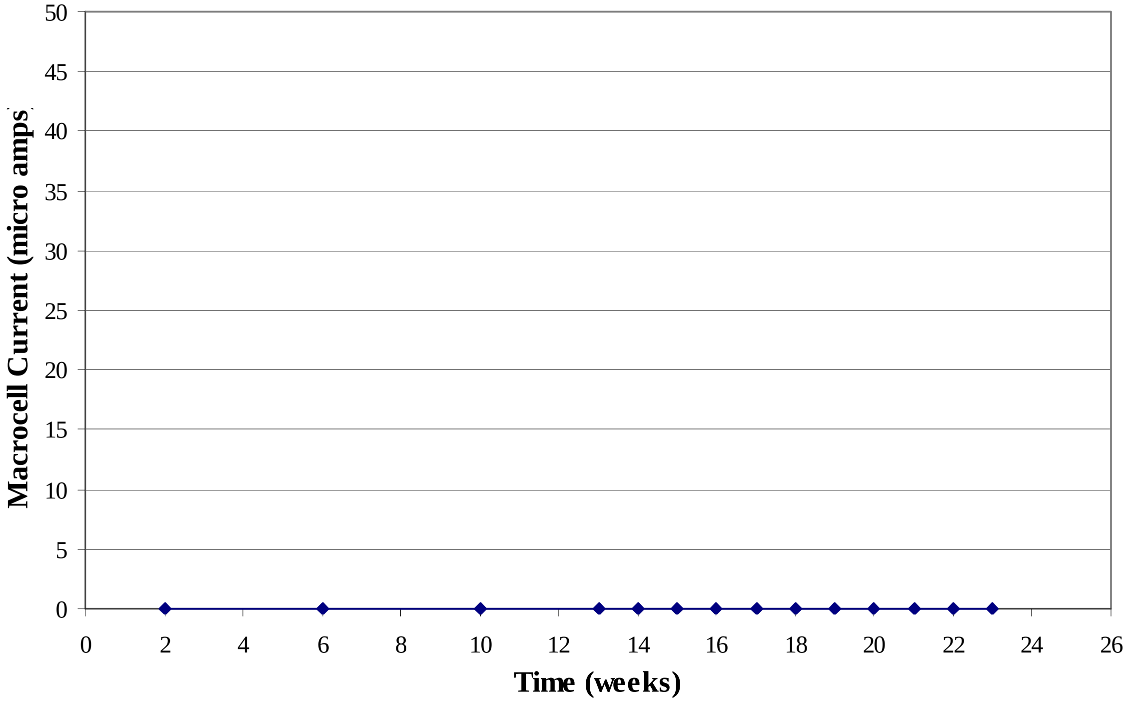


Figure 47: I-0.44-5-G Average Macrocell Current vs. Time

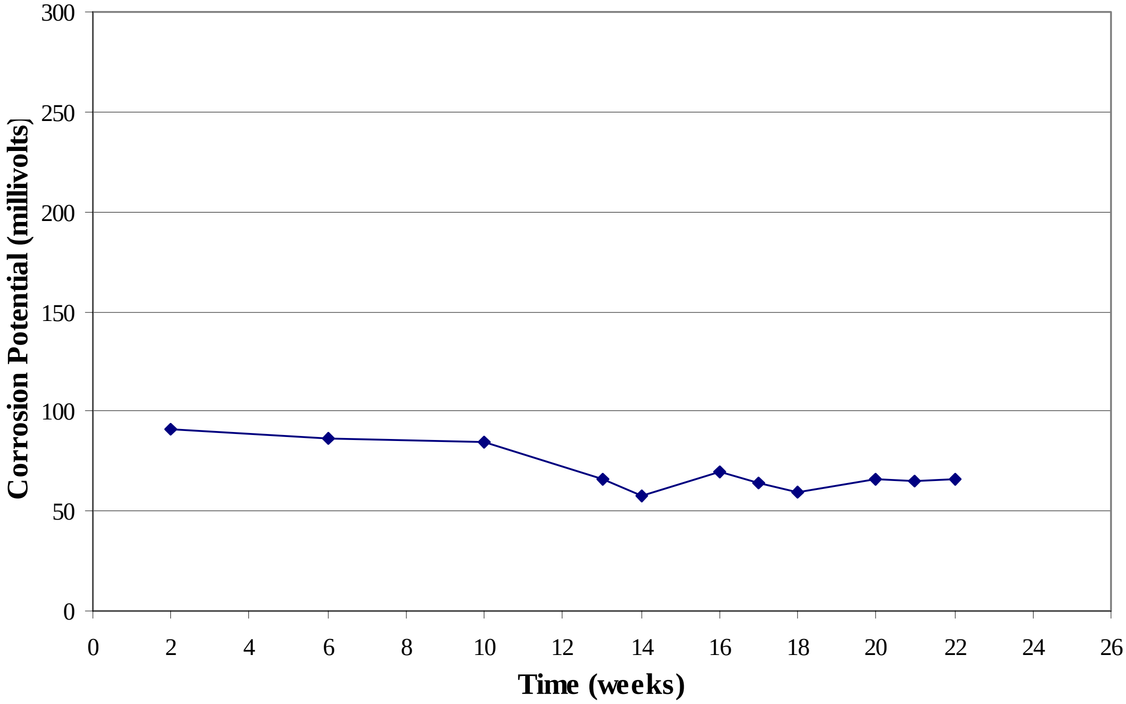


Figure 48: I-0.44-5-G Average Corrosion Potential vs. Time

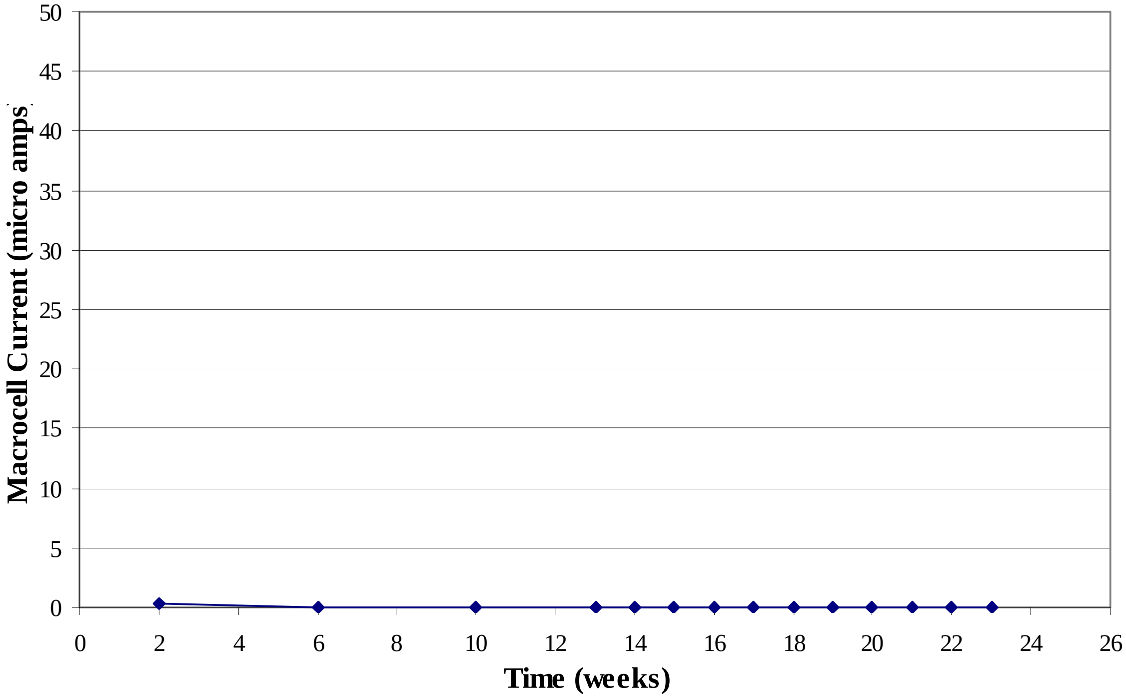


Figure 49: I-0.44-5-M Average Macrocell Current vs. Time

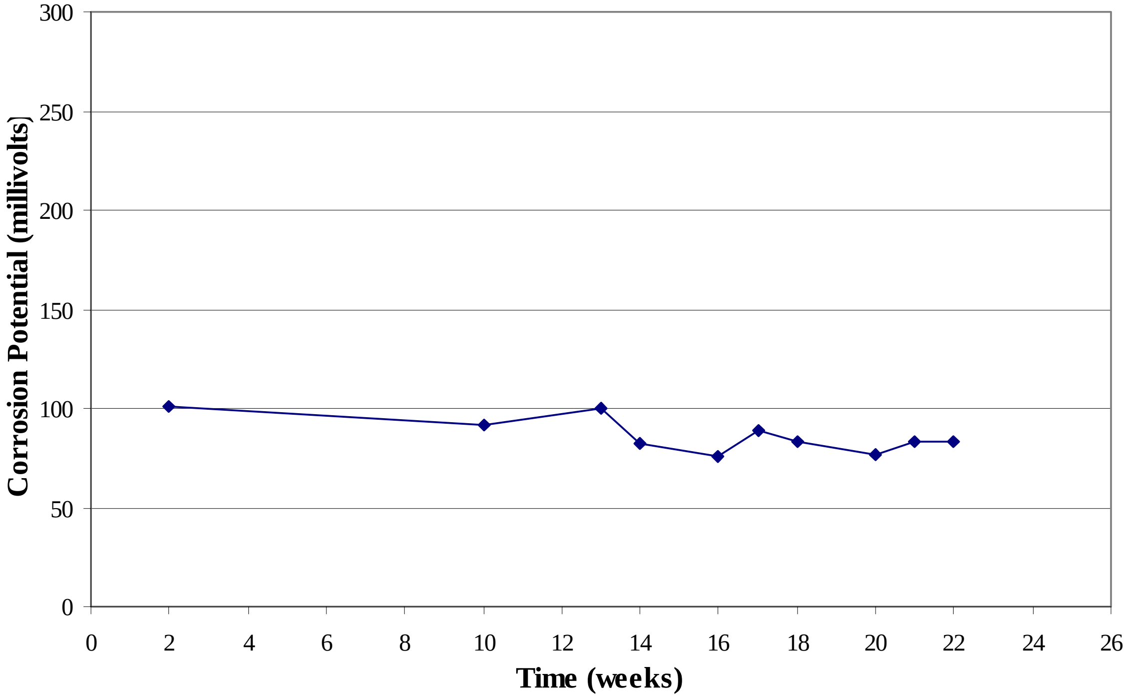


Figure 50: I-0.44-5-M Average Corrosion Potential vs. Time

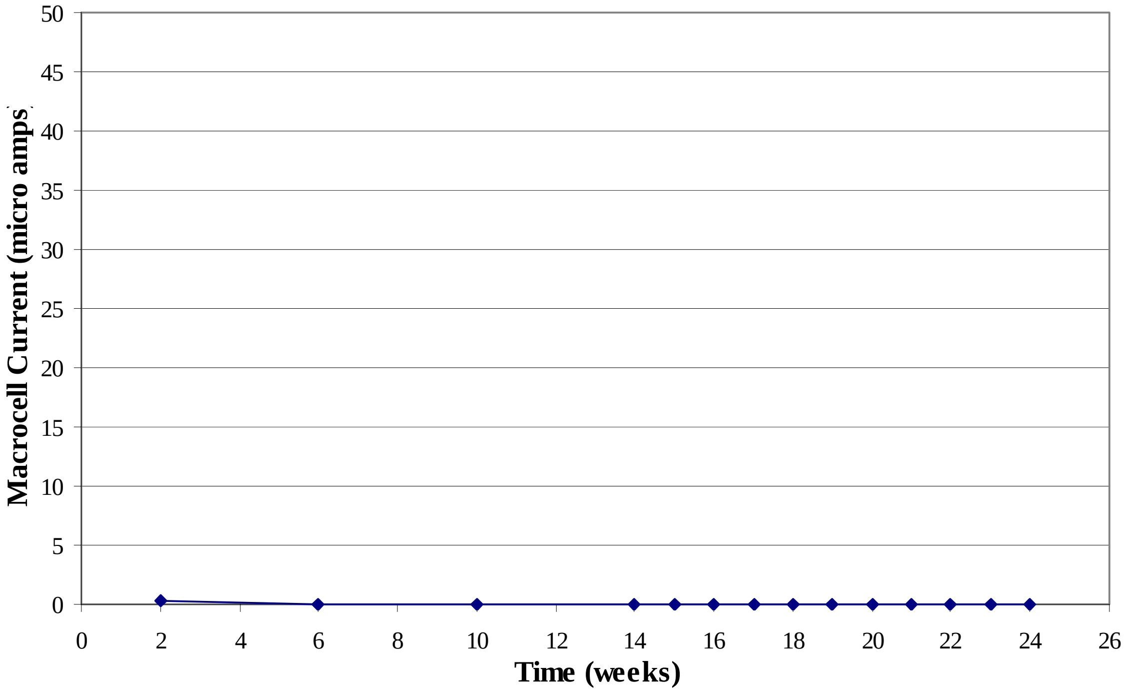


Figure 51: I-0.48-0-G Average Macrocell Current vs. Time

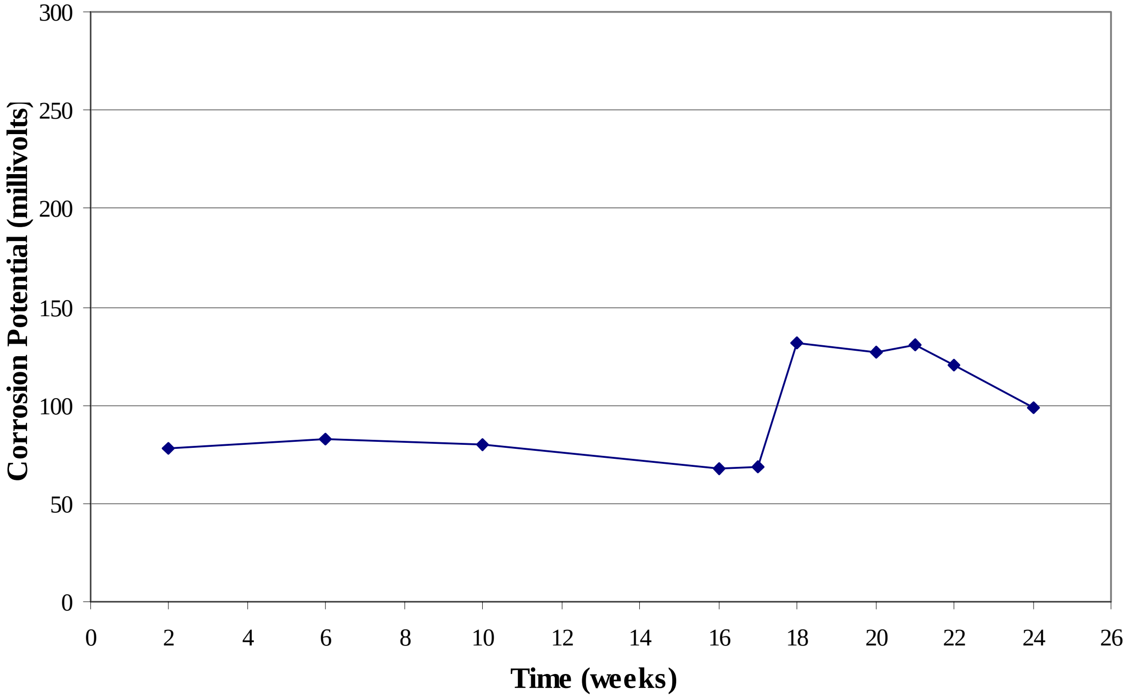


Figure 52: I-0.48-0-G Average Corrosion Potential vs. Time

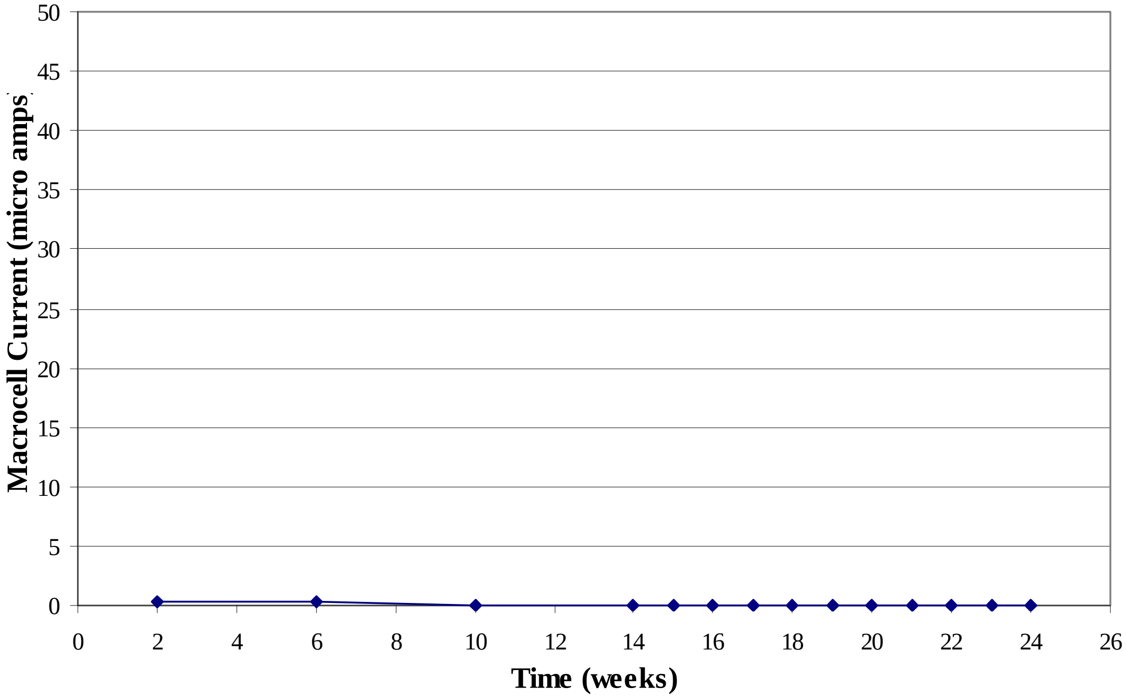


Figure 53: I-0.48-0-M Average Macrocell Current vs. Time

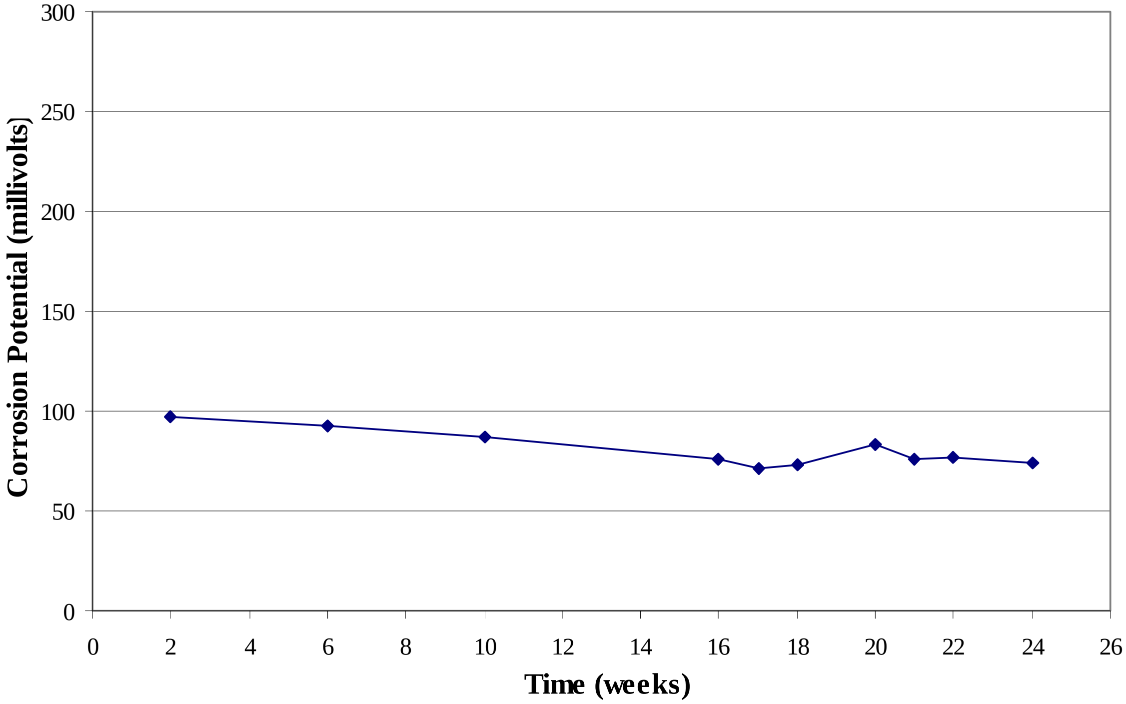


Figure 54: I-0.48-0-M Average Corrosion Potential vs. Time

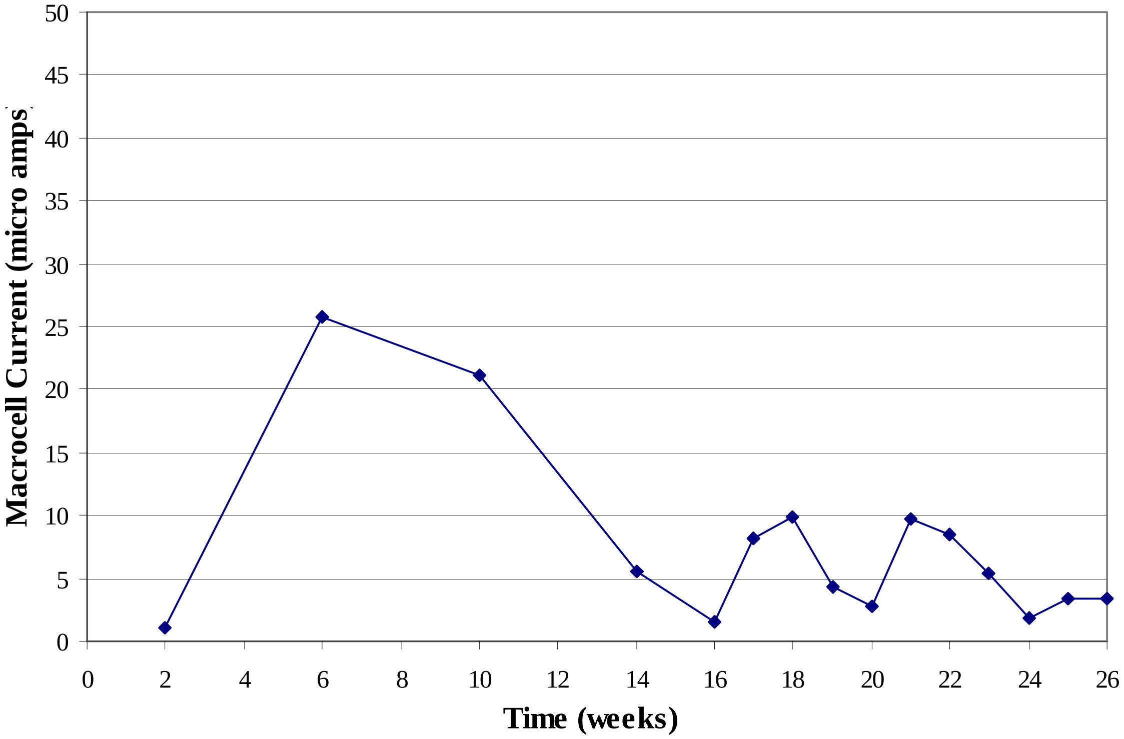


Figure 55: I-0.48-2-B Average Macrocell Current vs. Time

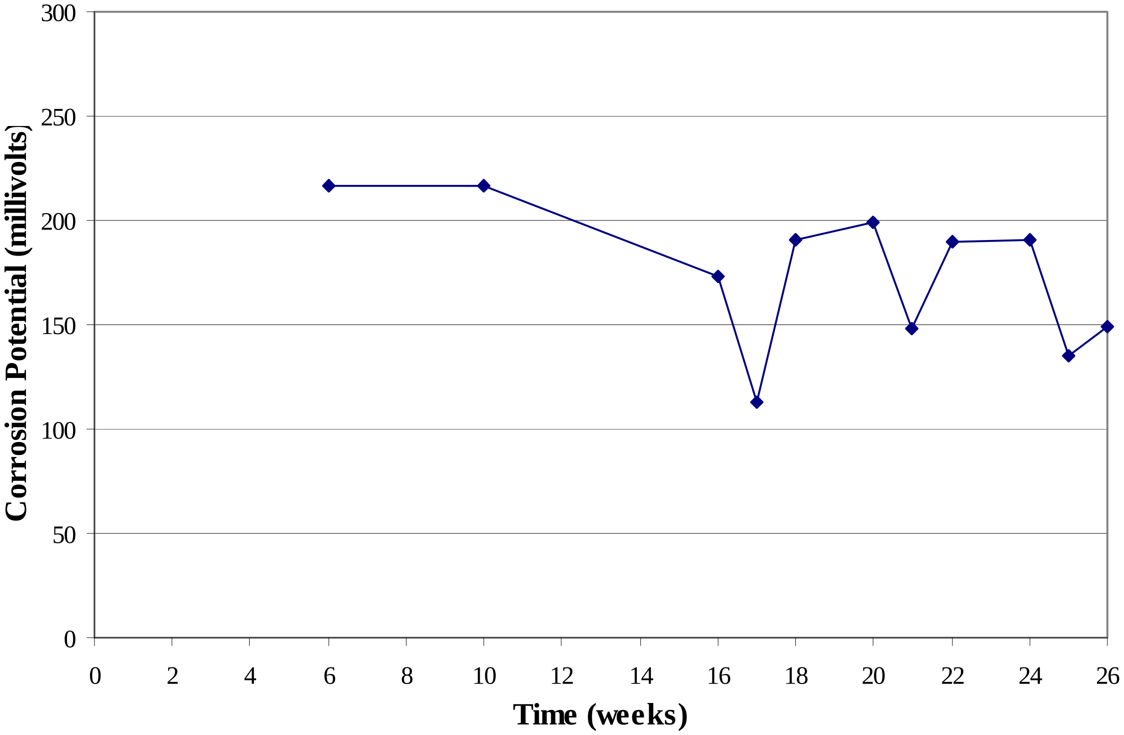


Figure 56: I-0.48-2-B Average Corrosion Potential vs. Time

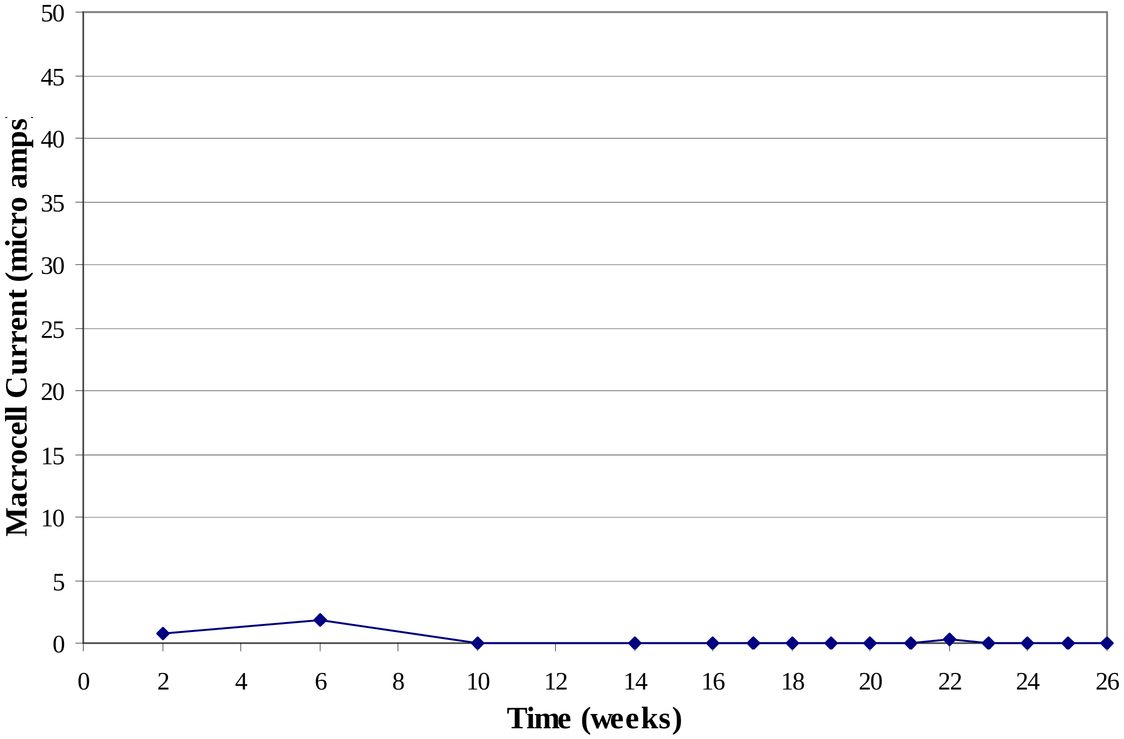


Figure 57: I-0.48-2-M Average Macrocell Current vs. Time

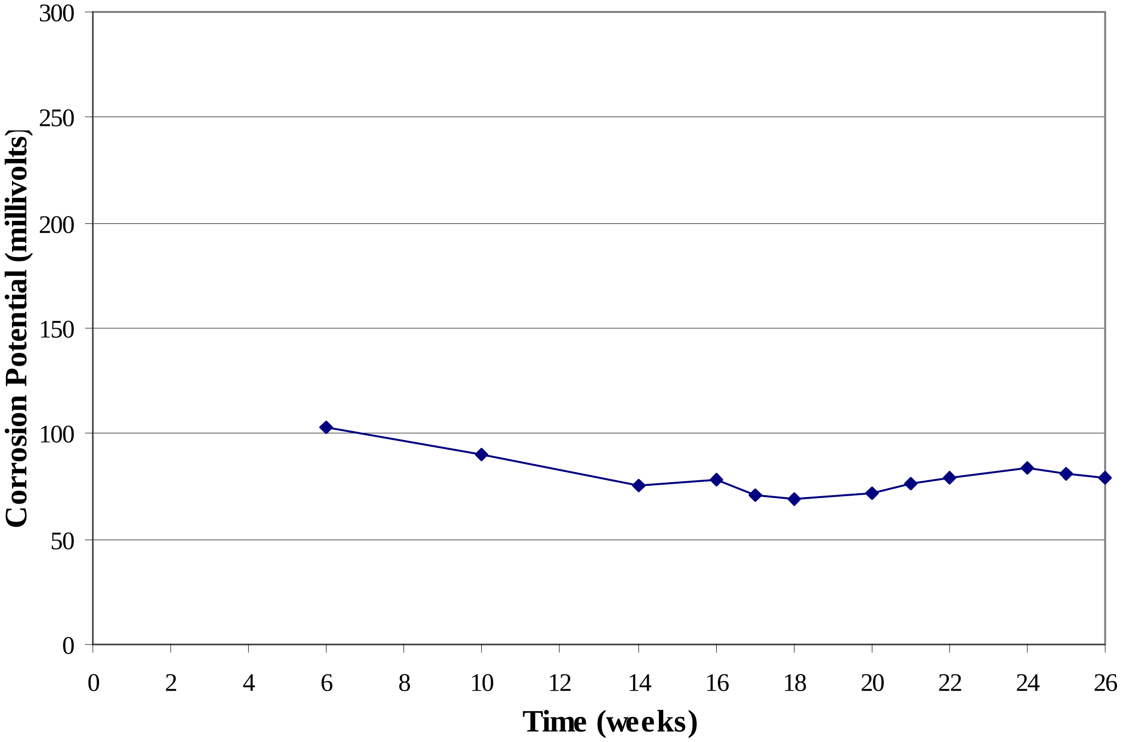


Figure 58: I-0.48-2-M Average Corrosion Potential vs. Time

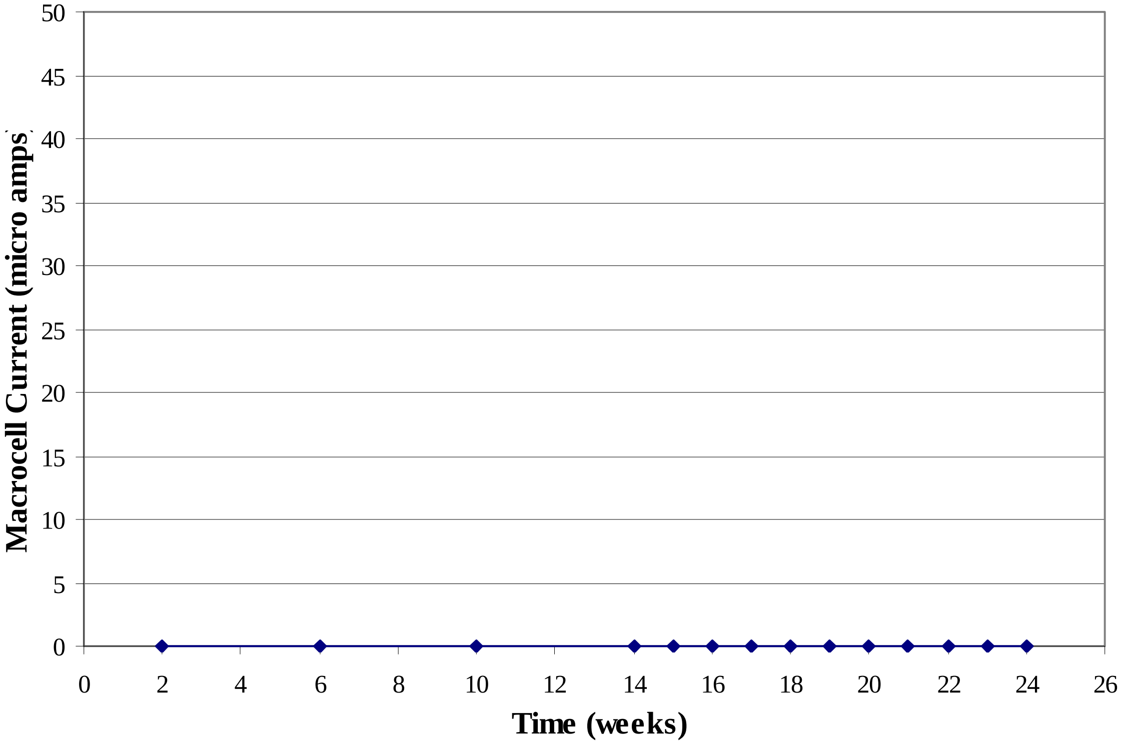


Figure 59: NI-0.40-0-B Average Macrocell Current vs. Time

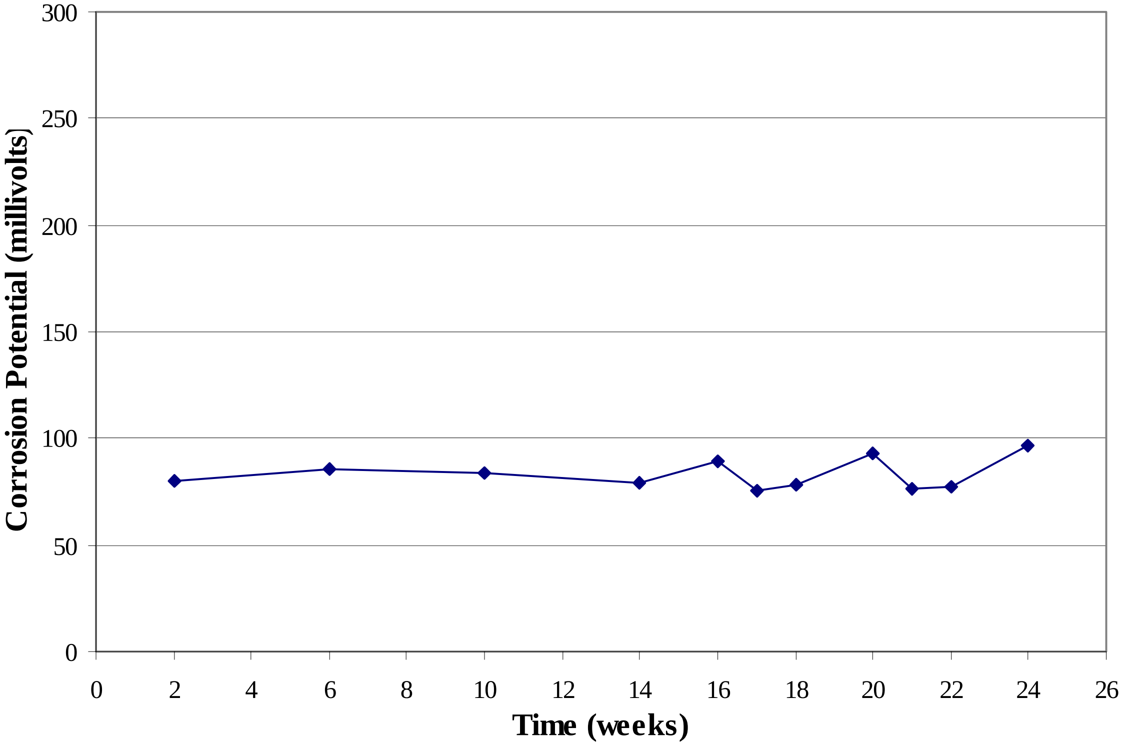


Figure 60: NI-0.40-0-B Average Corrosion Potential vs. Time

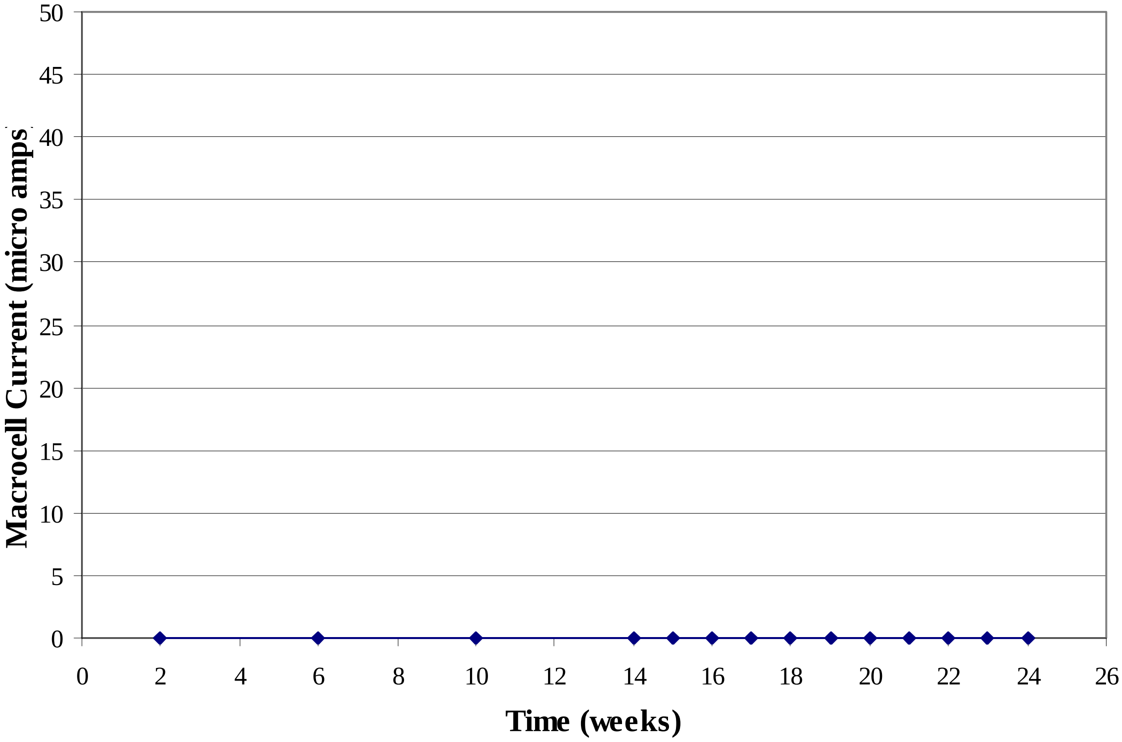


Figure 61: NI-0.40-0-G Average Macrocell Current vs. Time

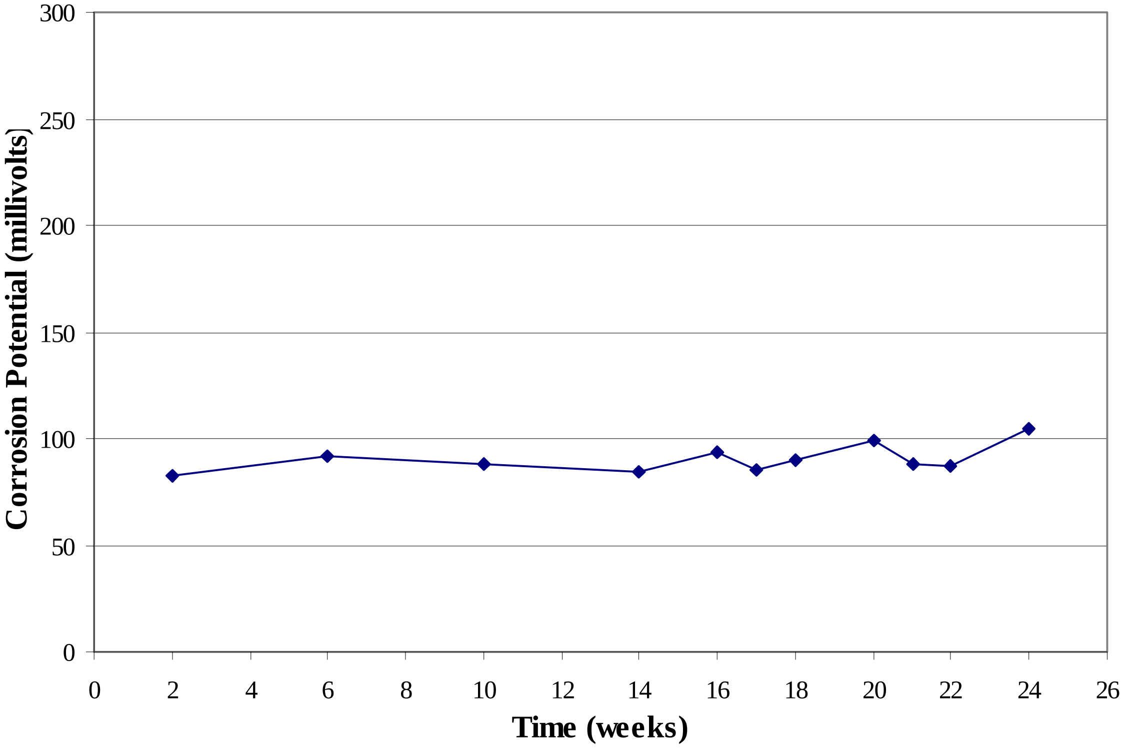


Figure 62: NI-0.40-0-G Average Corrosion Potential vs. Time

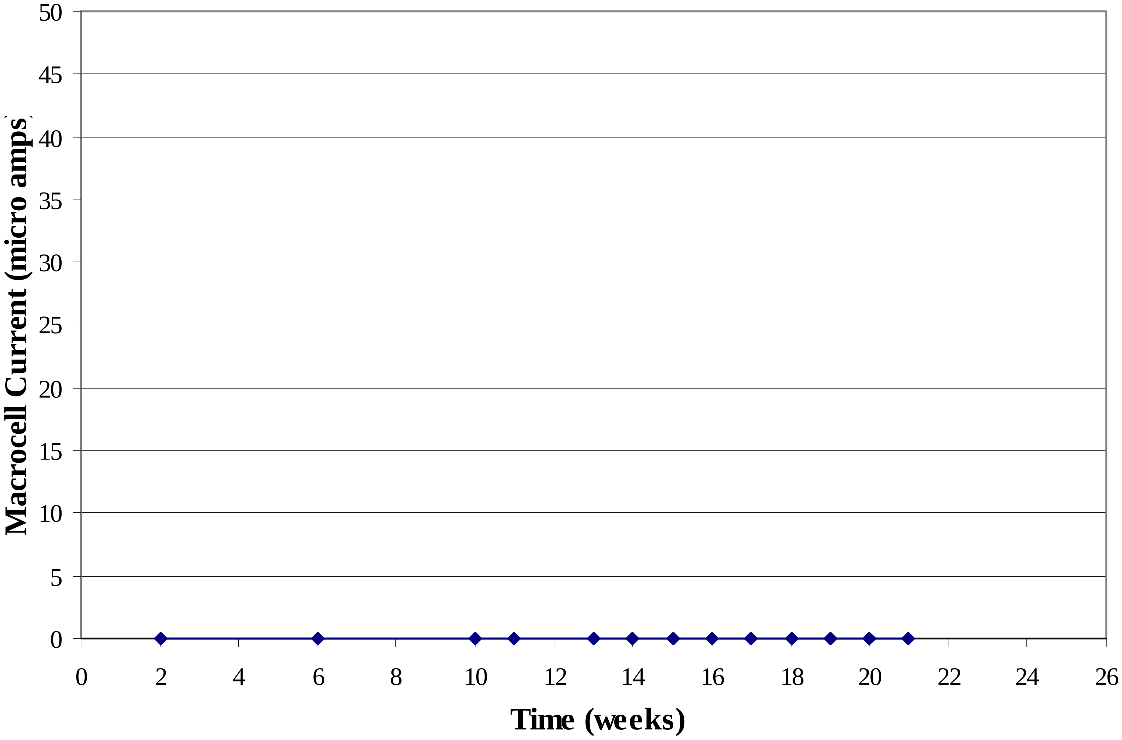


Figure 63: NI-0.40-2-G Average Macrocell Current vs. Time

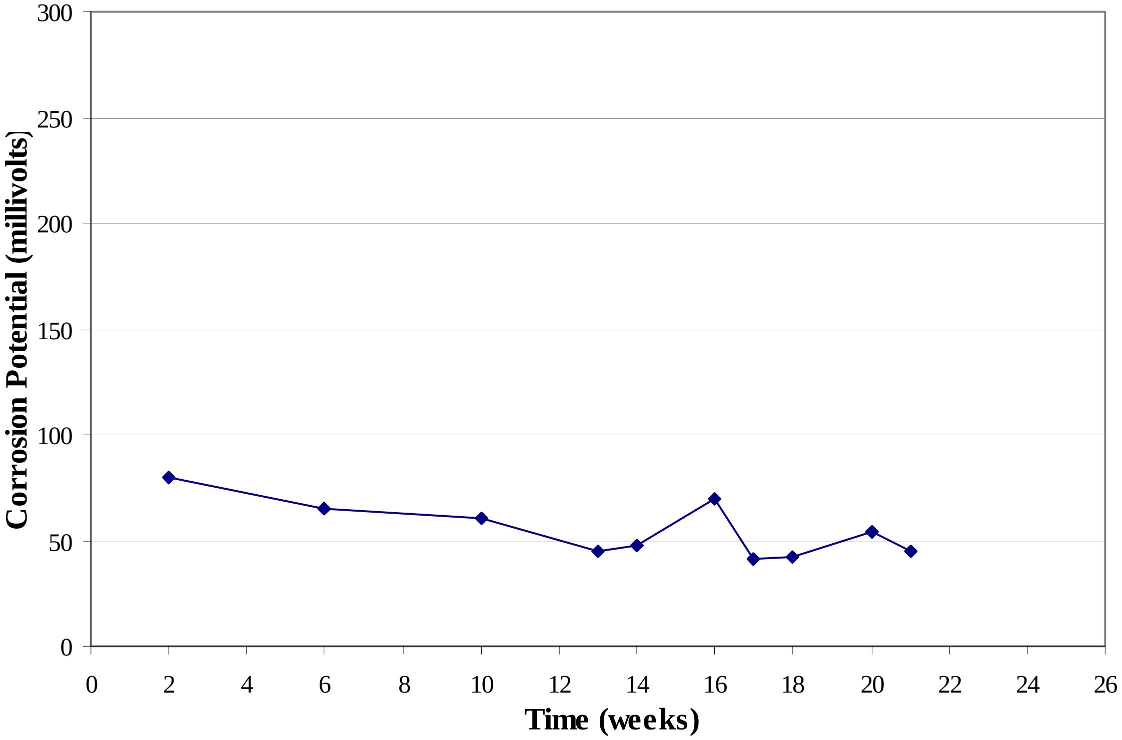


Figure 64: NI-0.40-2-G Average Corrosion Potential vs. Time

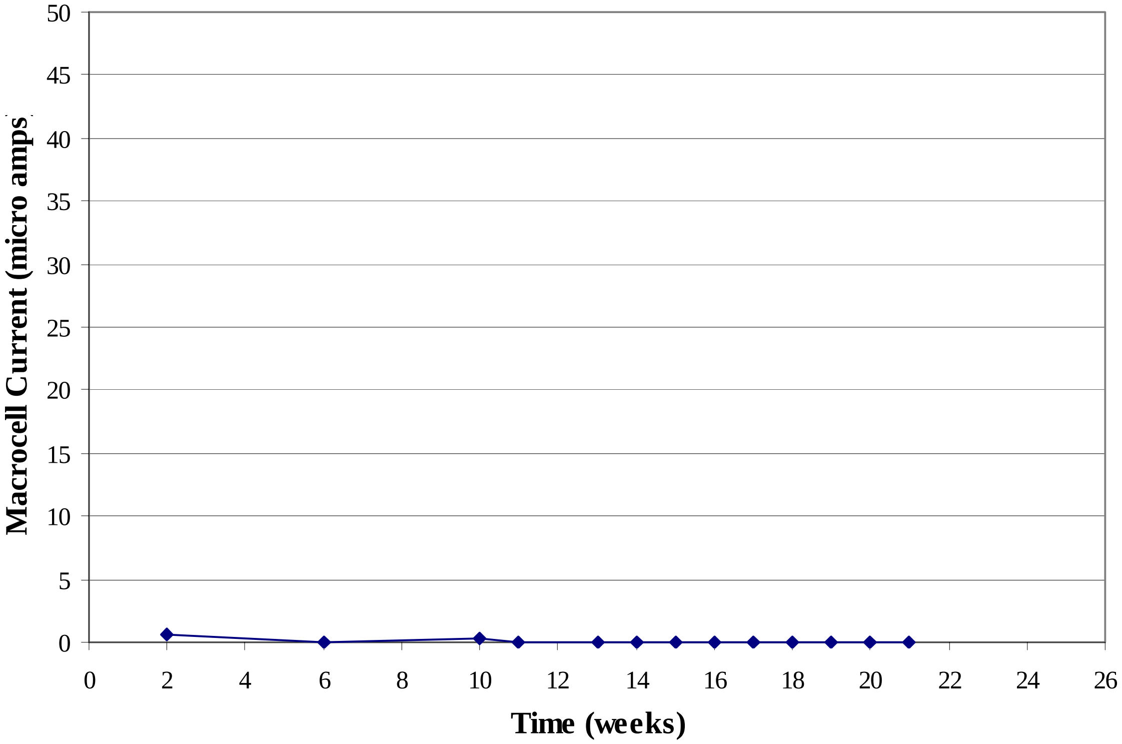


Figure 65: NI-0.40-2-M Average Macrocell Current vs. Time

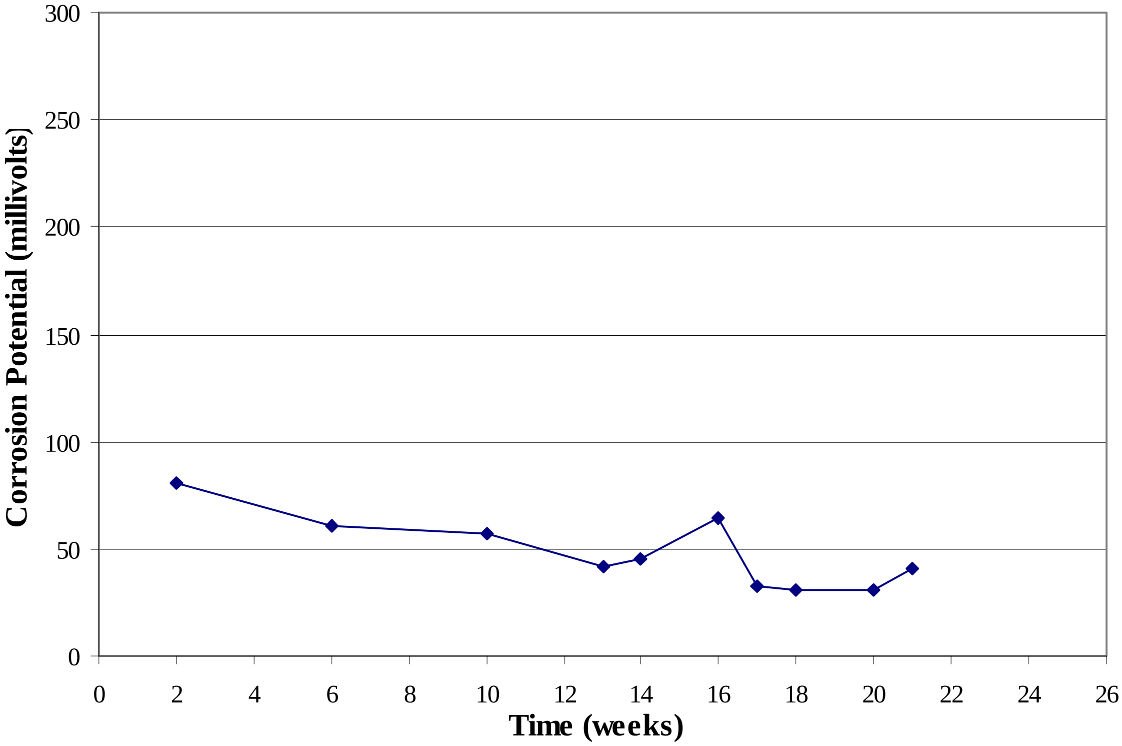


Figure 66: NI-0.40-M Average Corrosion Potential vs. Time

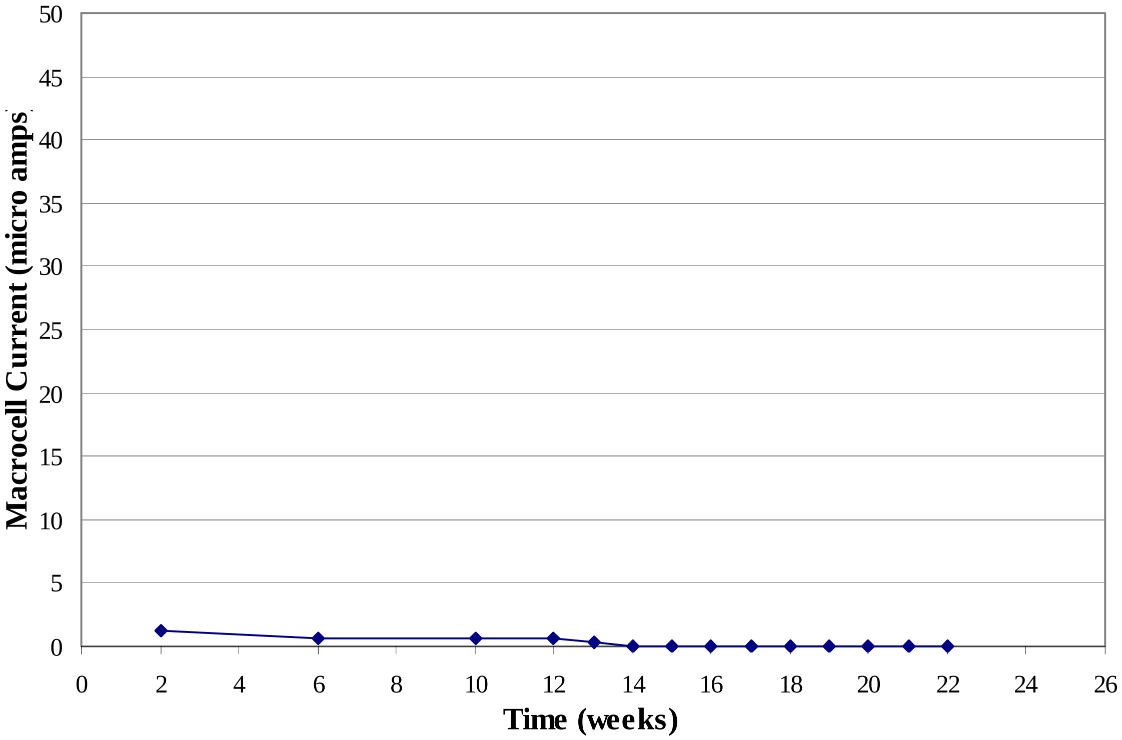


Figure 67: NI-0.44-2-B Average Macrocell Current vs. Time

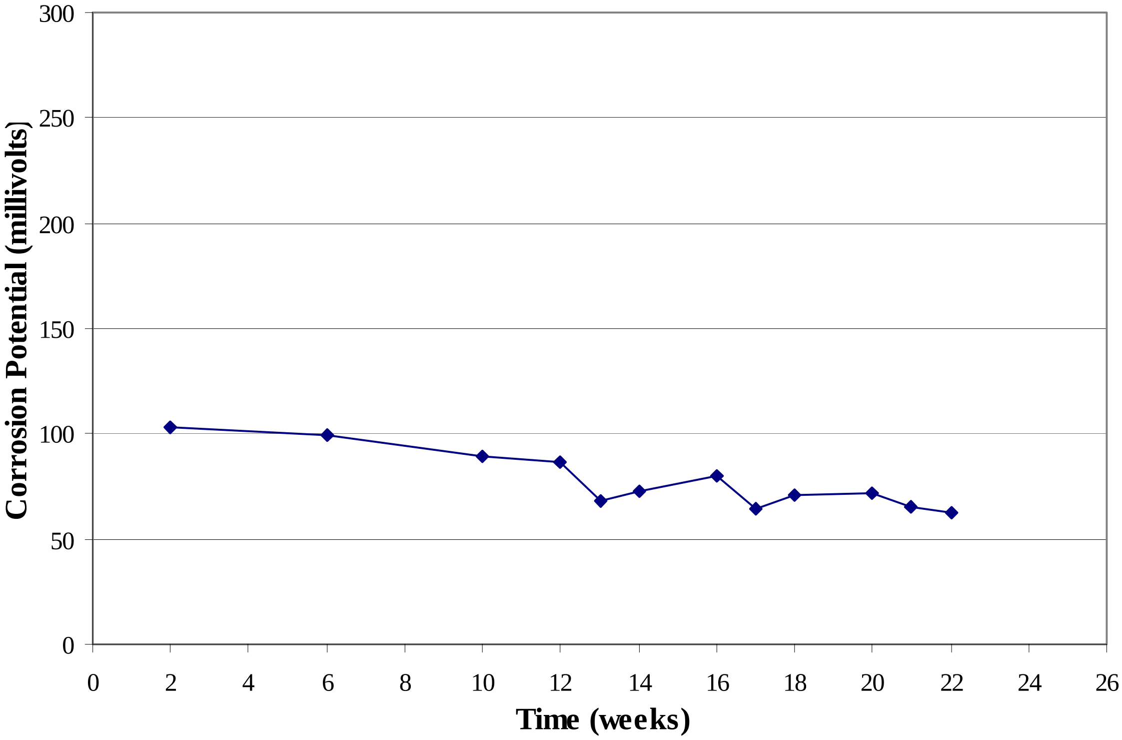


Figure 68: NI-0.44-2-B Average Corrosion Potential vs. Time

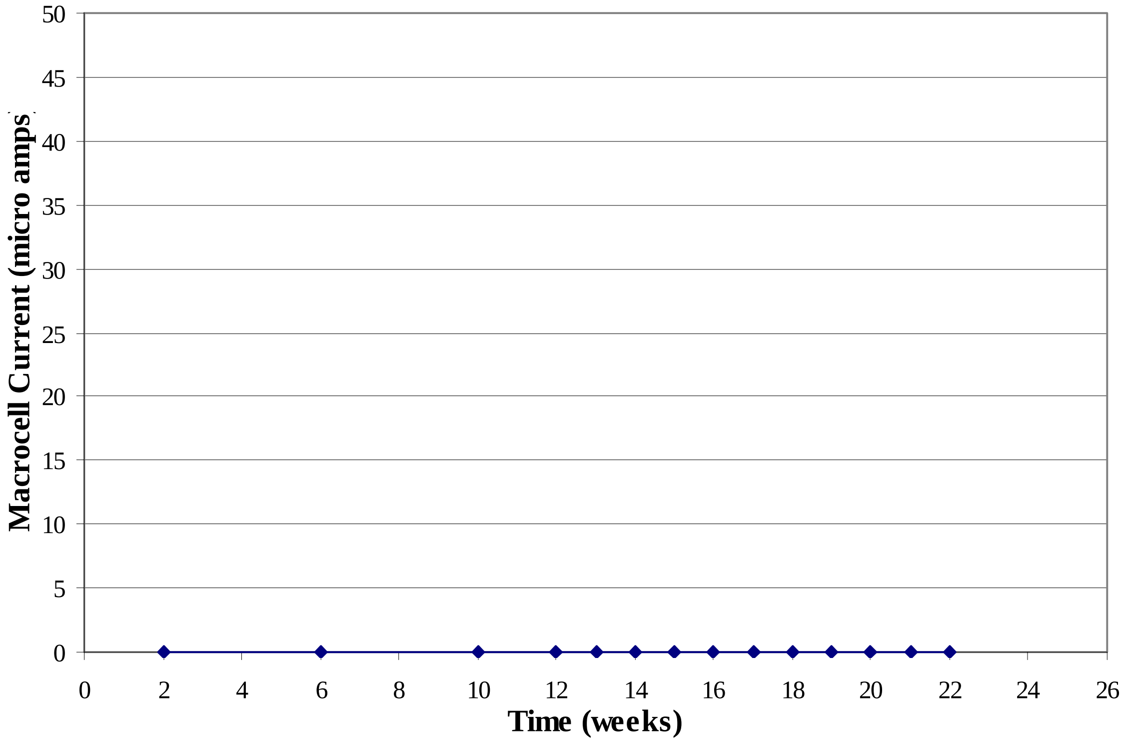


Figure 69: NI-0.44-2-G Average Macrocell Current vs. Time

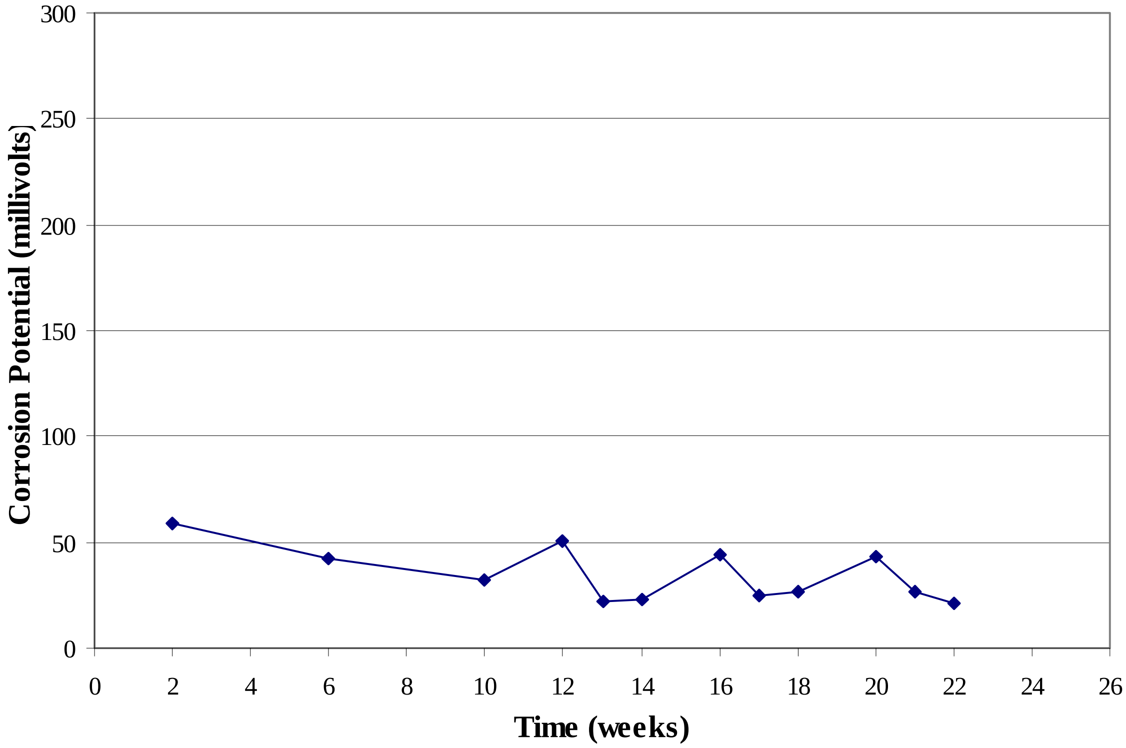


Figure 70: NI-0.44-2-G Average Corrosion Potential vs. Time

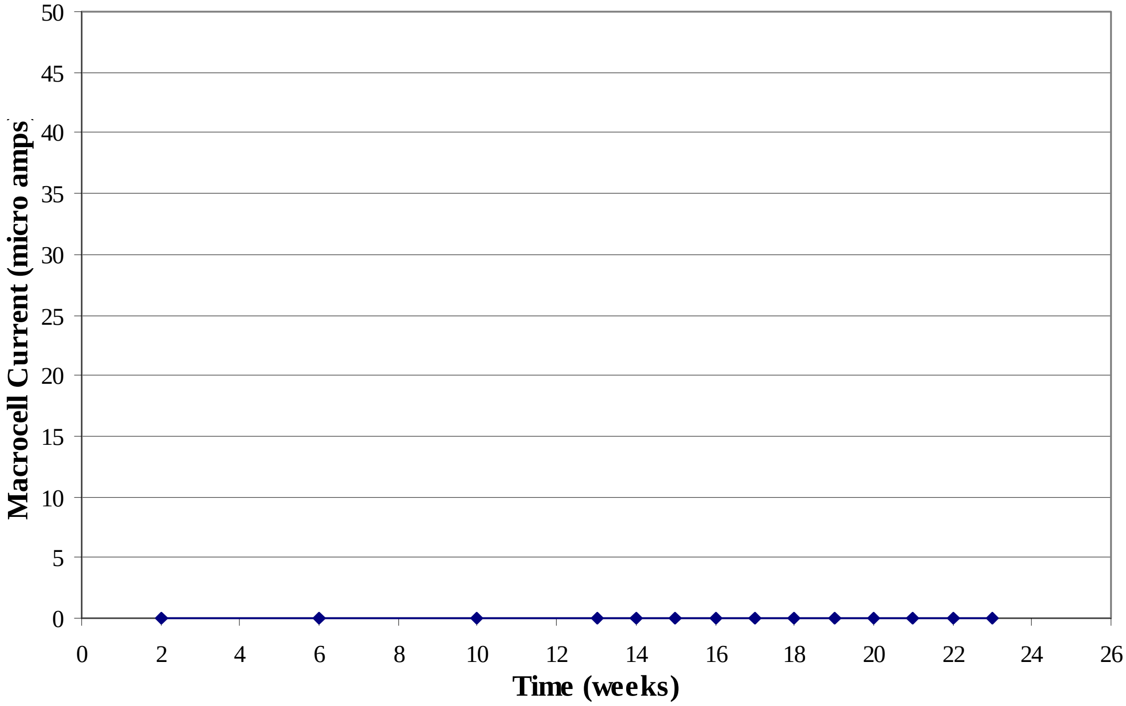


Figure 71: NI-0.44-5-G Average Macrocell Current vs. Time

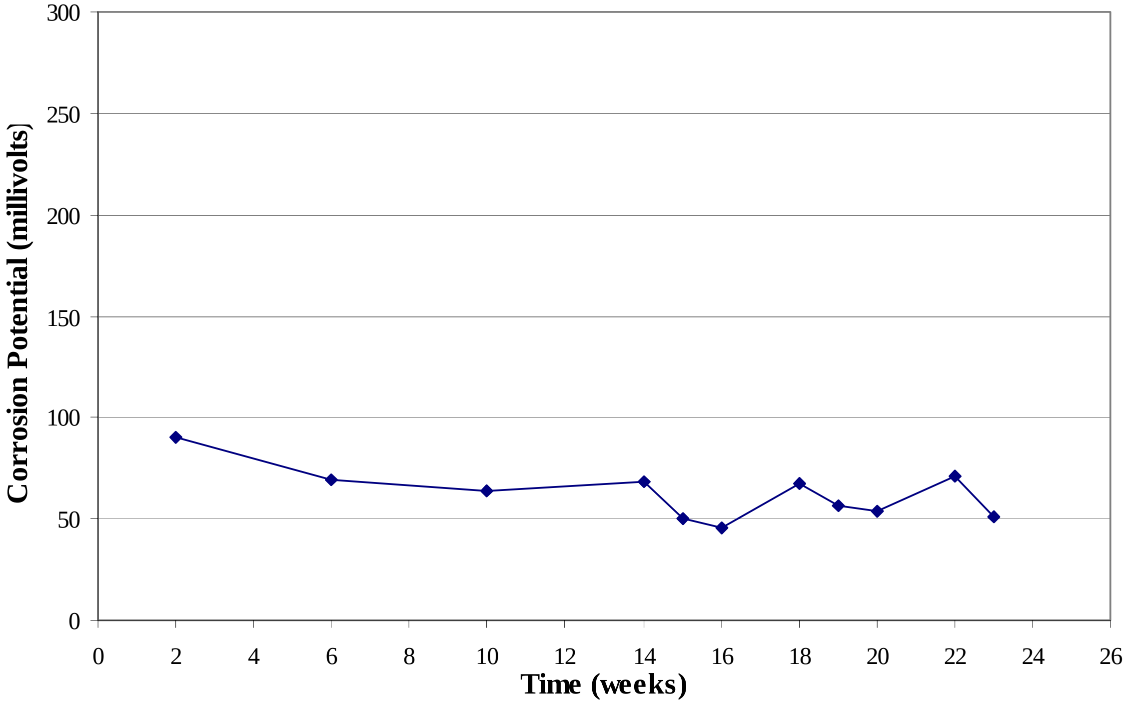


Figure 72: NI-0.44-5-G Average Corrosion Potential vs. Time

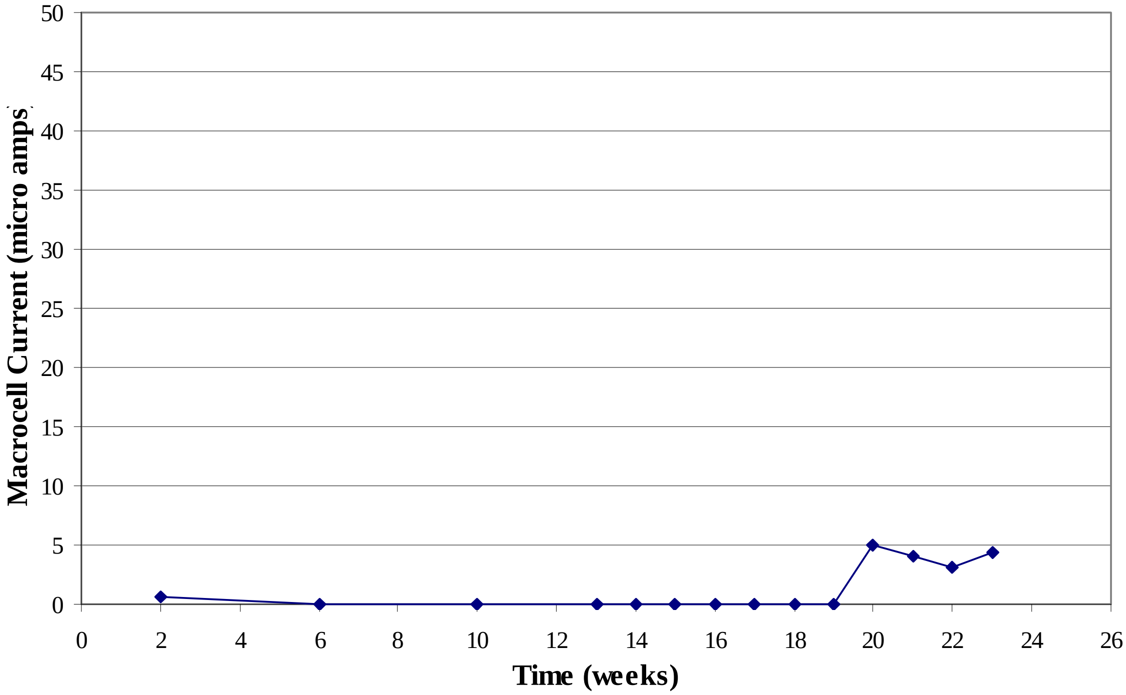


Figure 73: NI-0.44-5-M Average Macrocell Current vs. Time

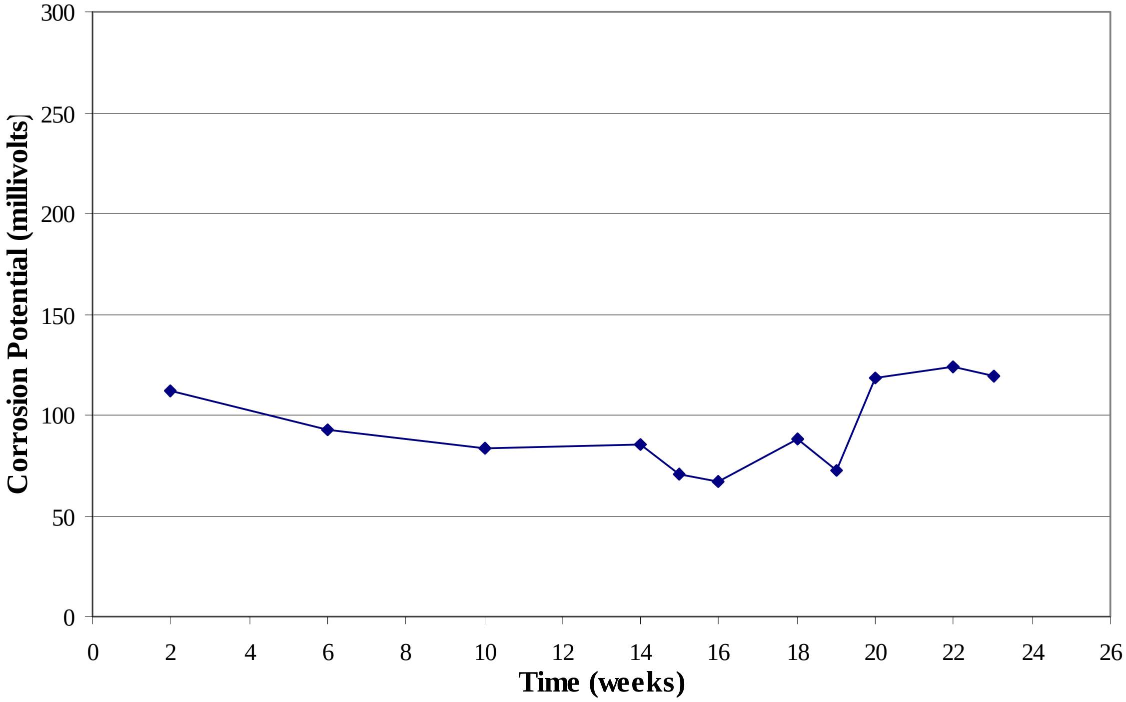


Figure 74: NI-0.44-5-M Average Corrosion Potential vs. Time

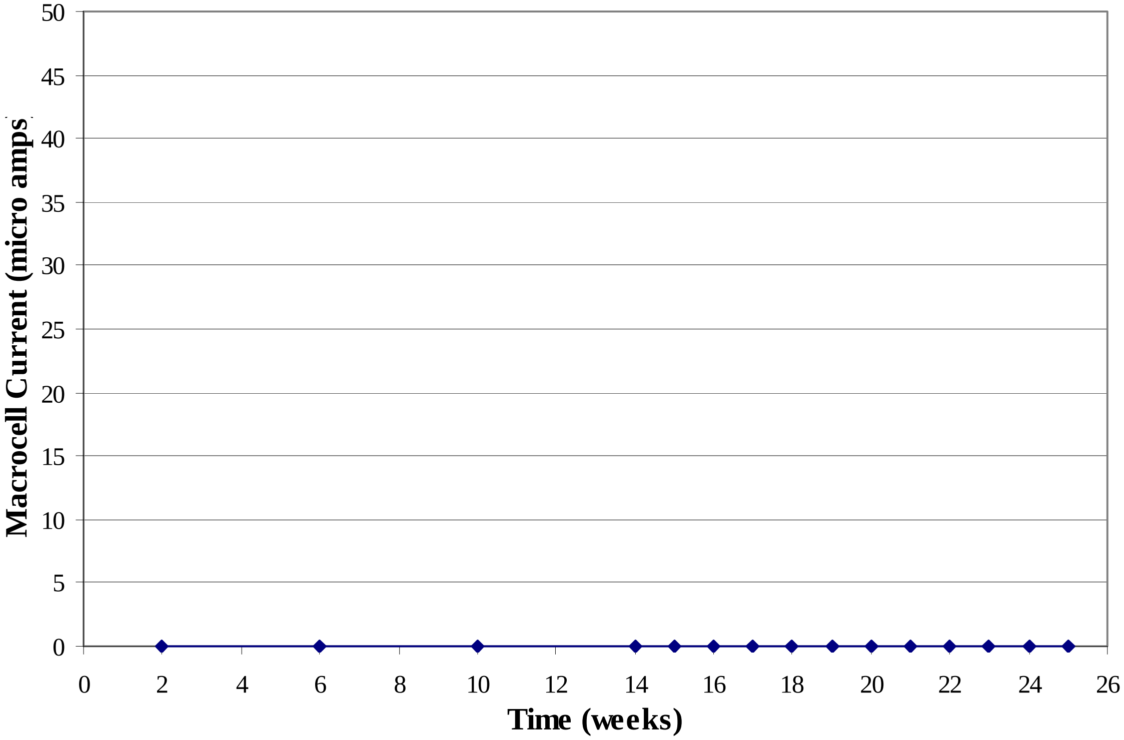


Figure 75: NI-0.48-0-G Average Macrocell Current vs. Time

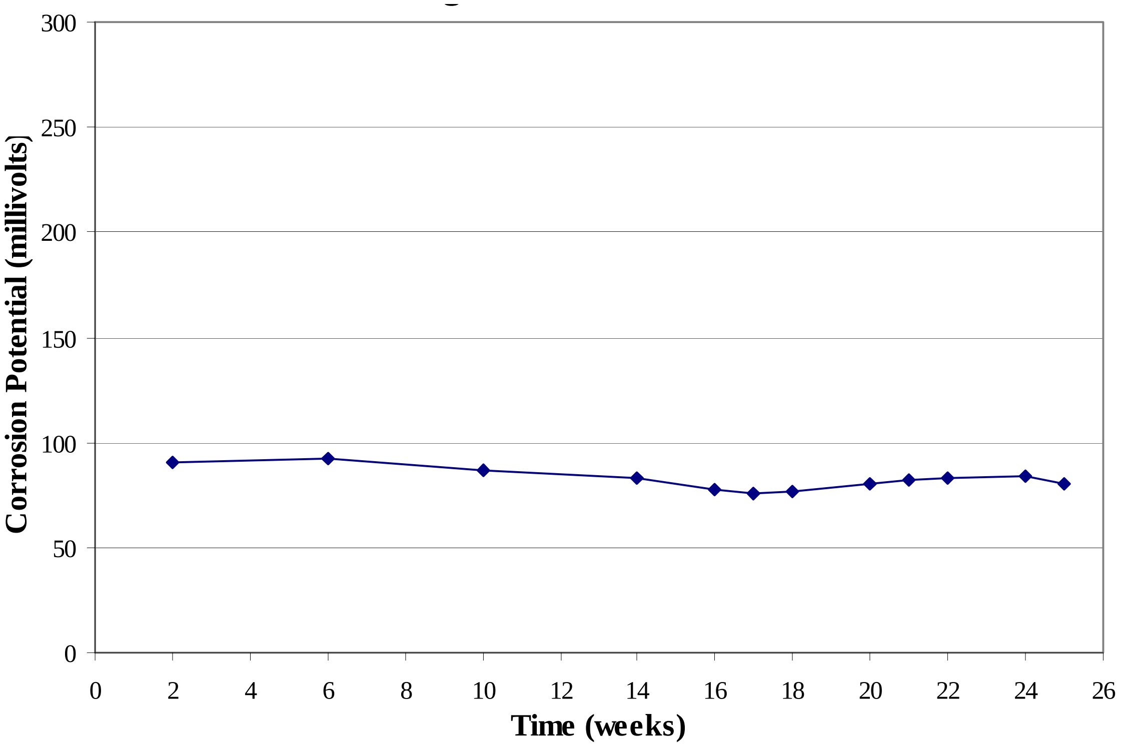


Figure 76: I-0.48-0-G Average Corrosion Potential vs. Time

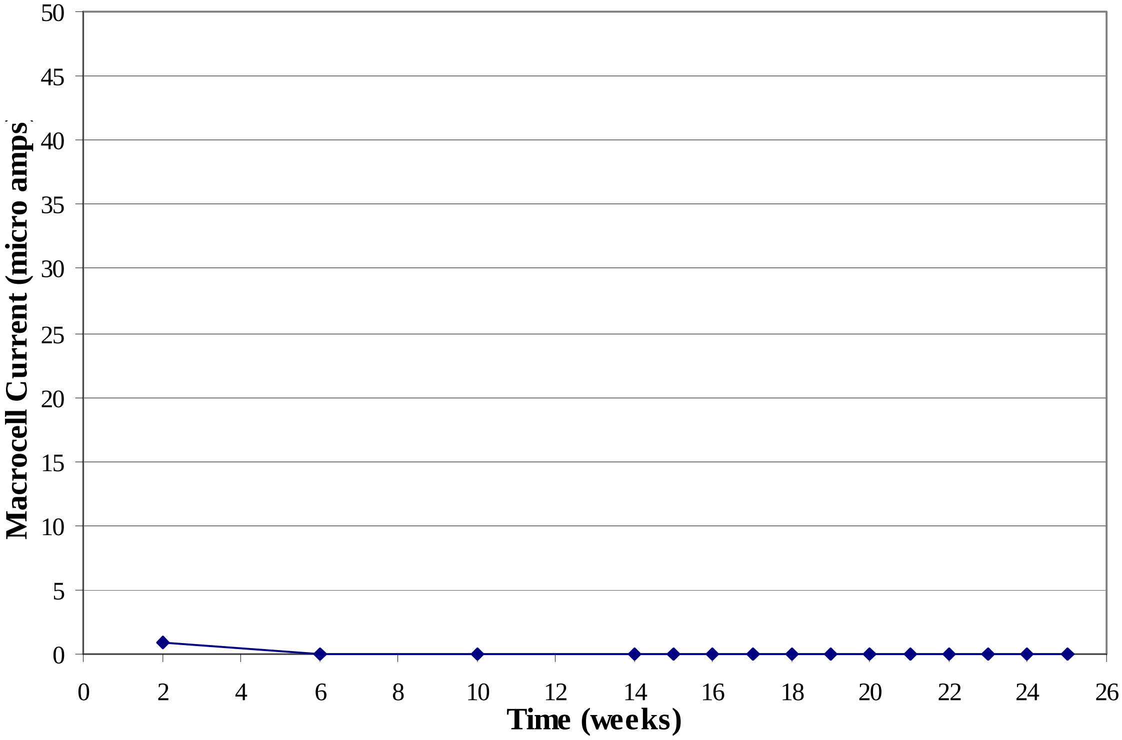


Figure 77: NI-0.48-0-M Average Macrocell Current vs. Time

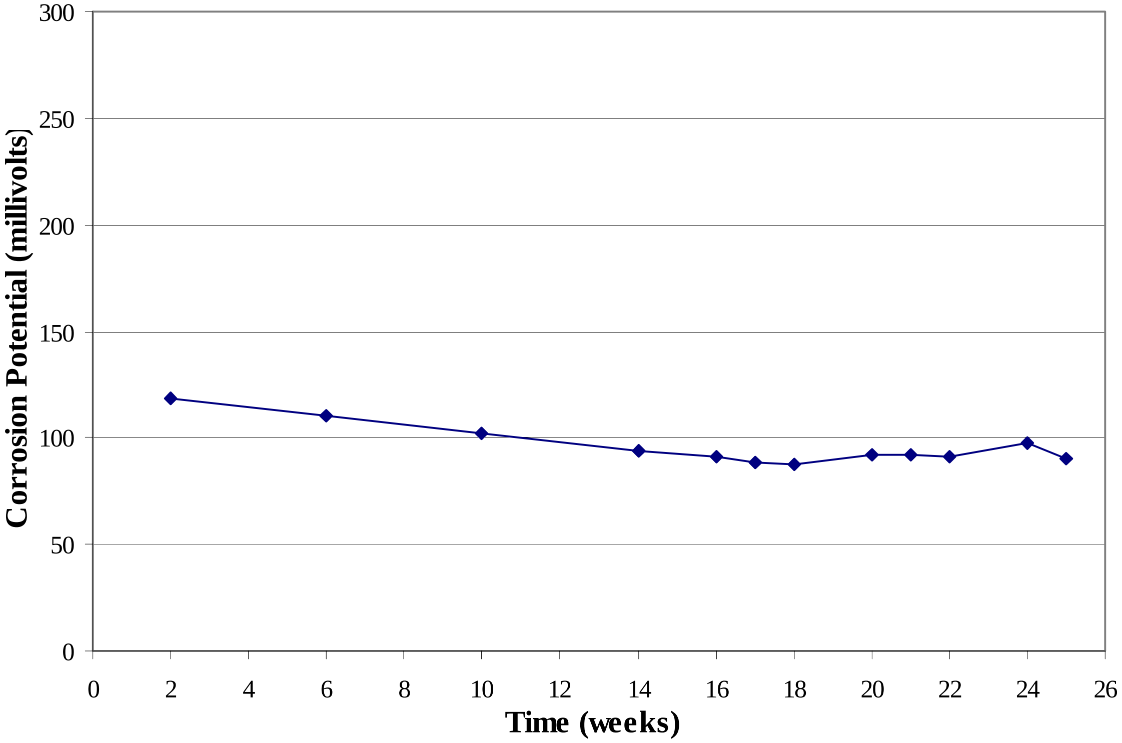


Figure 78: NI-0.48-0-M Average Corrosion Potential vs. Time

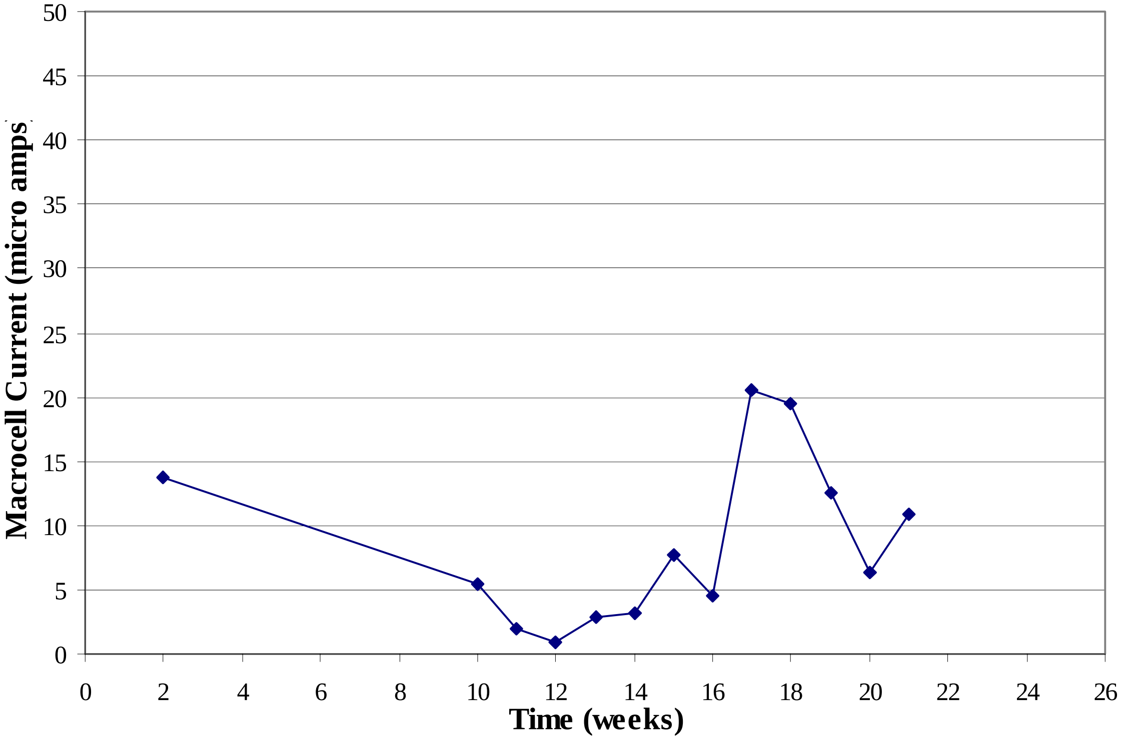


Figure 79: NI-0.48-5-B Average Macrocell Current vs. Time

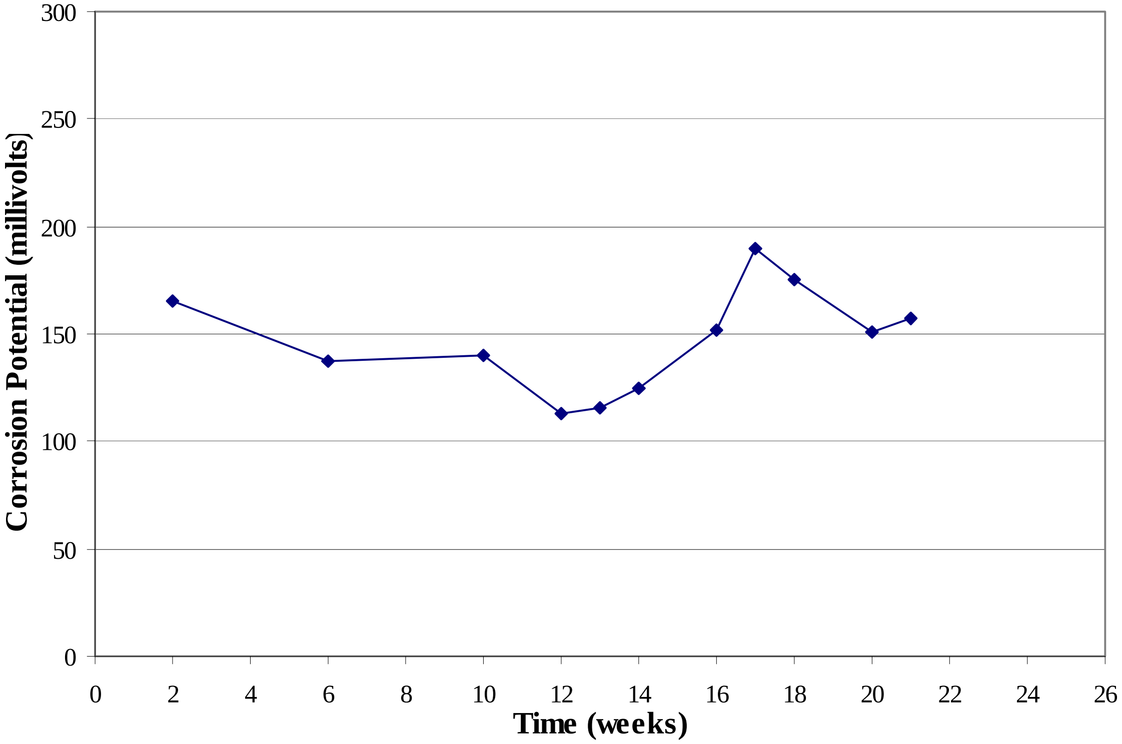


Figure 80: NI-0.48-5-B Average Corrosion Potential vs. Time

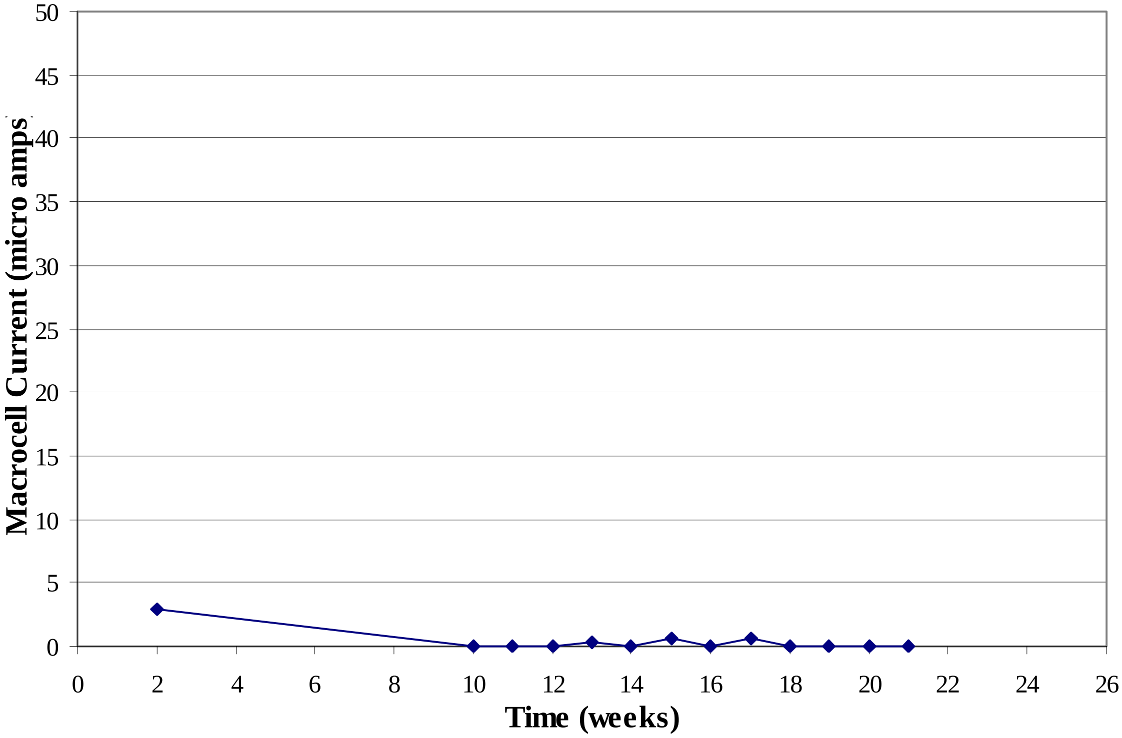


Figure 81: NI-0.48-5-G Average Macrocell Current vs. Time

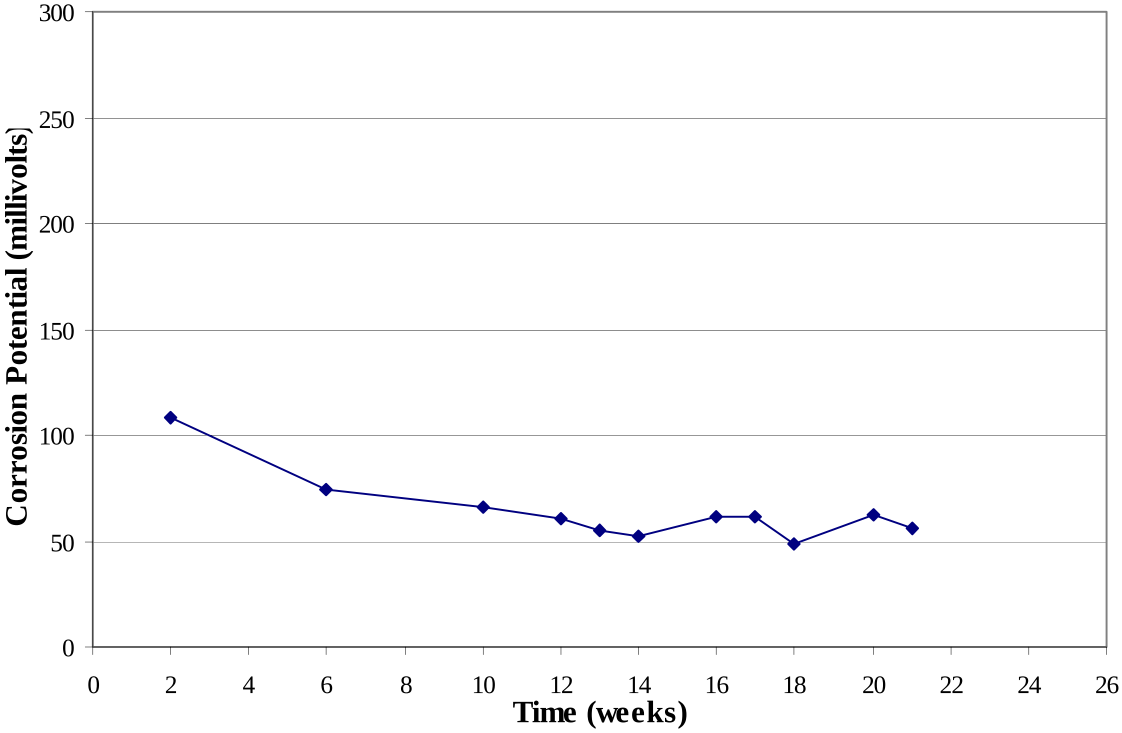


Figure 82: NI-0.48-5-G Average Corrosion Potential vs. Time

4.2 Results of Tension Tests of MMFX Reinforcement and Grade 60 Reinforcing Bars

The results of tension tests of MMFX and Grade 60 reinforcement are shown below in Tables 4.2 – 4.5. Because there is no defined yield point for MMFX steel, yield strength was calculated at the 0.2% offset method and the 0.7% strain method.

Elastic modulus, yield strength, yield strain, and ultimate strength were measured by the extensometer test setup. The LVDT test setup was used to measure ultimate strength and percent elongation. Yield stress of the black steel was able to be calculated because a defined yield point was evident. There was no defined yield point for MMFX steel. A 0.2% offset yield stress was not able to be calculated because the LVDT setup does not accurately measure strain. The LVDT setup does not accurately measure strain because the moduli calculated from the results of the black steel tests are much larger than the known modulus of steel. The know modulus of steel is 29,000 ksi but the modulus calculated was 10,000 ksi greater than this.

Table 4.2 Results of Tension Tests of MMFX Reinforcement From Extensometer Setup

Test	Elastic Modulus (ksi)	Yield Strength (ksi)		Strain at 0.2% offset yield stress (in/in)	Ultimate Strength (ksi)
		0.2% Offset	0.7% Strain		
1	28,206	125	130	0.00643	178.2
2	28,117	122	127	0.00634	176.7
3	27,441	127	130	0.00663	179.7
Average	27,921	124.7	129.0	0.00647	178.2
Std. Dev.	419	2.5	1.7	0.00015	1.5

Table 4.3 Results of Tension Tests of Grade 60 Reinforcement From Extensometer Setup

Test	Elastic Modulus (ksi)	Yield Strength (ksi)	Strain at yield (in/in)	Ultimate Strength (ksi)
1	25,880	62.3	0.00245	83.9
2	30,444	64.3	0.00225	85.2
3	31,325	65.2	0.00215	88.7
Avg.	29,216	63.9	0.00228	85.9
Std. Dev.	2,923	1.5	0.00016	2.5

Table 4.4 Results of Tension Tests of MMFX Reinforcement From LVDT Setup

Test	Ultimate Strength (ksi)	Elongation in 4 in. (%)
1	179.8	8.4
2	177	7.5
3	185.7	7.9
Average	180.8	7.9
Std. Dev.	4.4	0.5

Table 4.5 Results of Tension Tests of Grade 60 Reinforcement From LVDT Setup

Test	Yield Strength (ksi)	Ultimate Strength (ksi)	Elongation in 4 in. (%)
1	65.2	87.9	17.7
2	64.3	87.0	16.6
3	66.2	86.2	16.9
Average	65.2	87.0	17.1
Std. Dev.	1.0	0.9	0.6

Stress-strain graphs were created from the data obtained from the tension testing. These graphs are shown in Figures 83 – 94. The full record of the data can be found in Appendix C. Only every tenth data point is shown for the extensometer test setup due to the large amount of data collected. Only every twentieth data point is shown for the LVDT test setup due to the large amount of data collected.

Figure 86 captures the entire test of an MMFX specimen. This is the only specimen in the extensometer test setup where the entire behavior from beginning to fracture was captured. The point at which the graph stops in figures 83, 84, 85, 86, & 88 is not when the bar fractured. This is the point when the displacement of the extensometer stopped increasing. The extension was either recorded as the same number repeated or a nonsensical number such as a negative number was repeated. The graphs of the LVDT setup show the entire test from beginning to fracture.

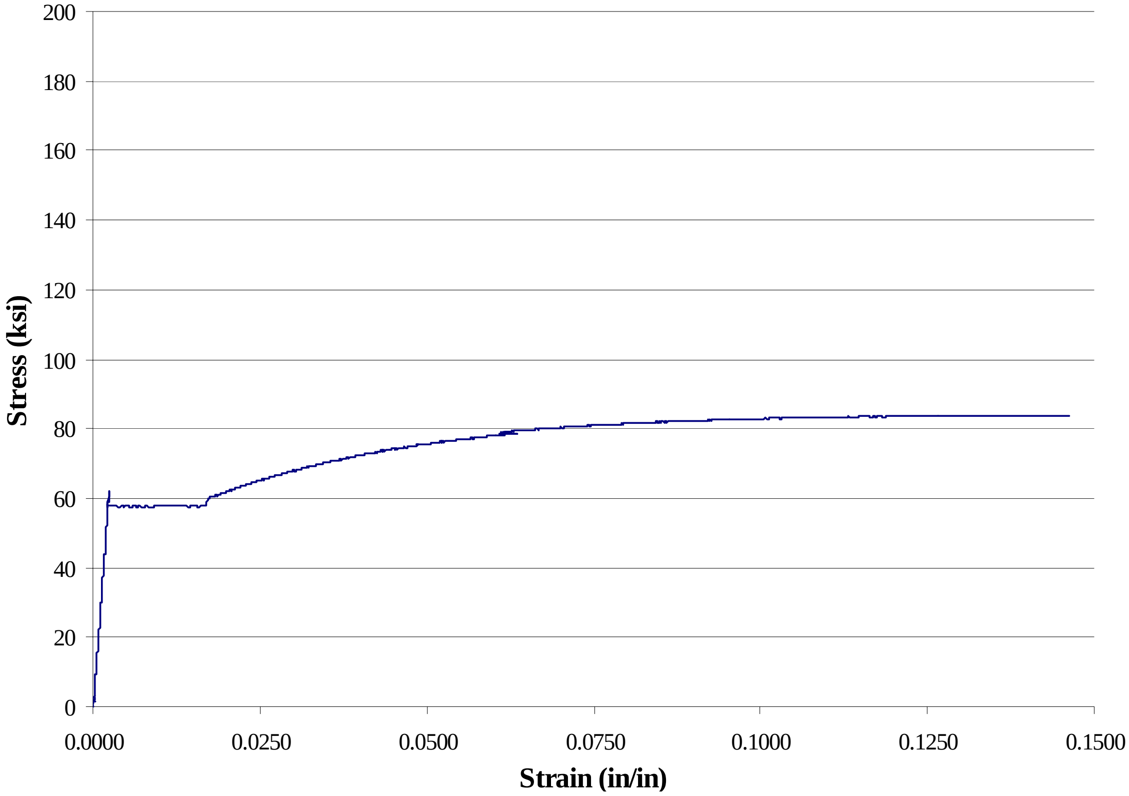


Figure 83: Stress-Strain Graph for Black Steel Tension Test 1 (Extensometer Setup)

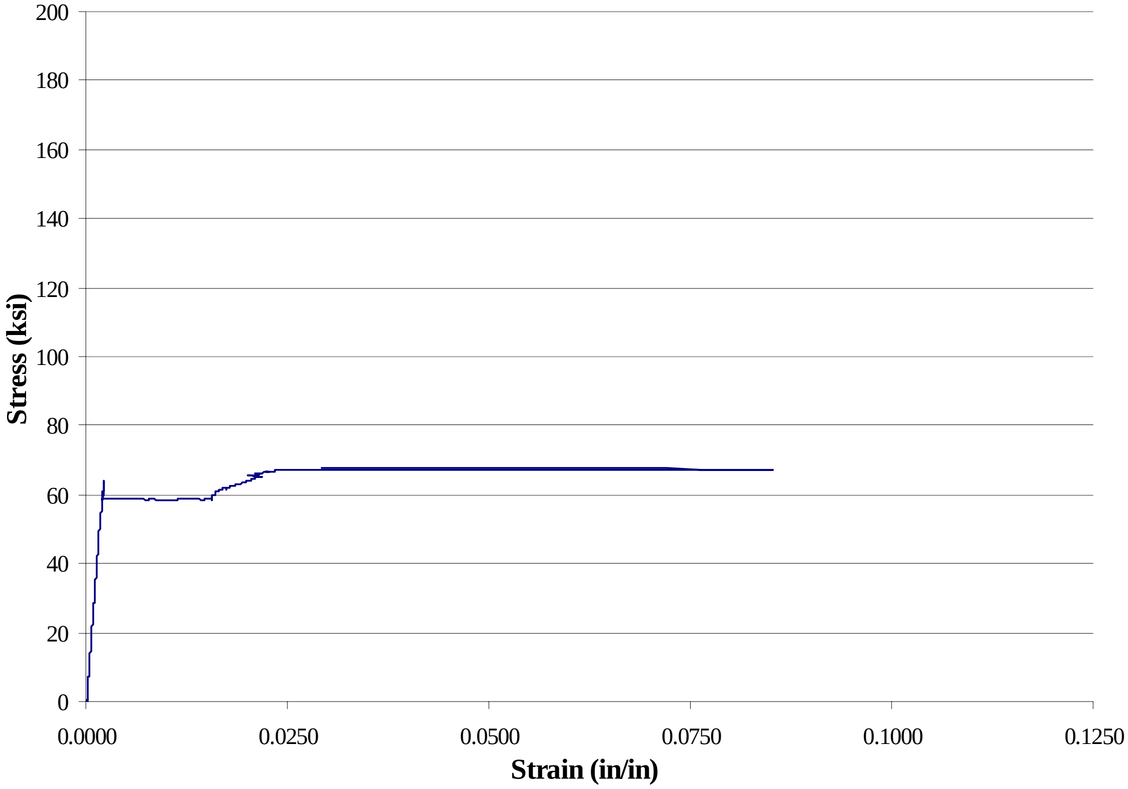


Figure 84: Stress-Strain Graph for Black Steel Tension Test 2 (Extensometer Setup)

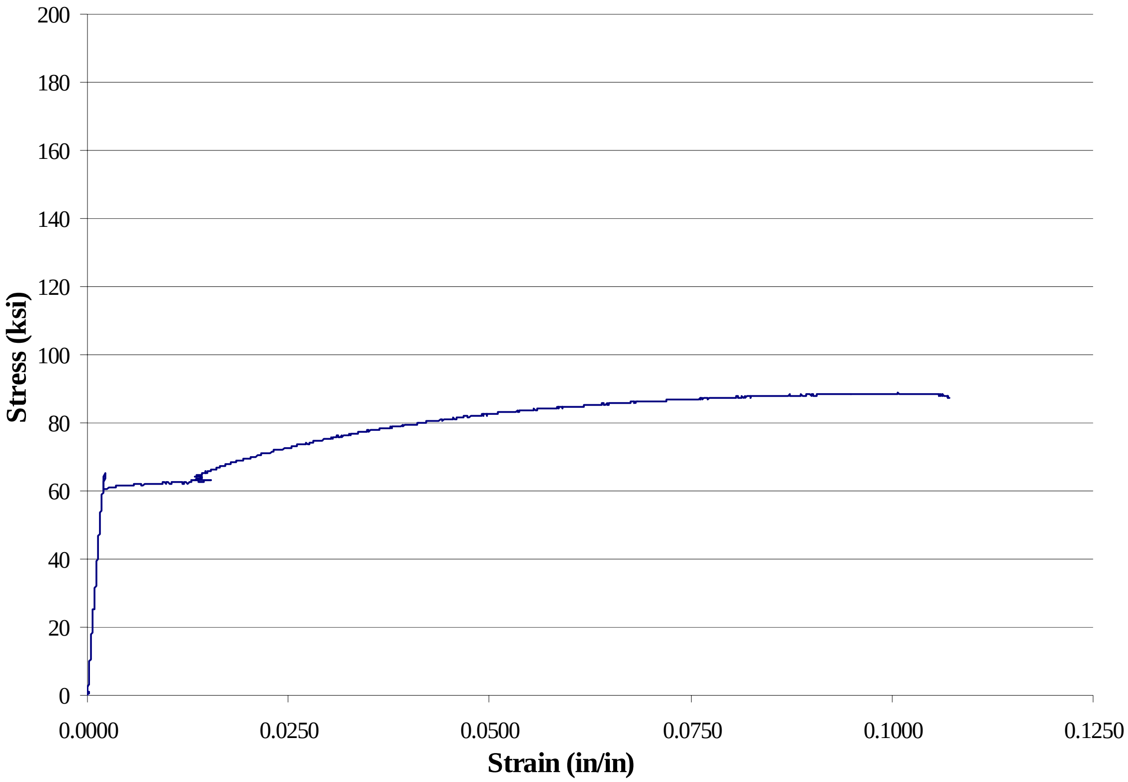


Figure 85: Stress-Strain Graph for Black Steel Tension Test 3 (Extensometer Setup)

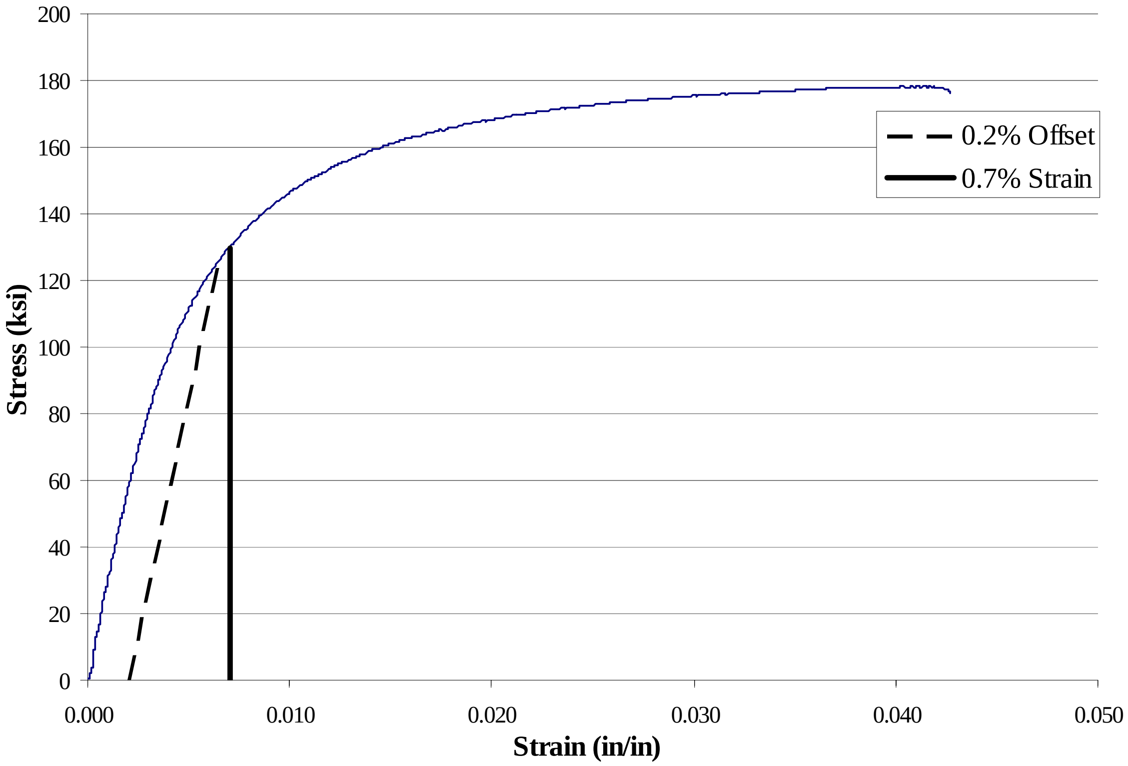


Figure 86: Stress-Strain Graph for MMFX Steel Tension Test 1 (Extensometer Setup)

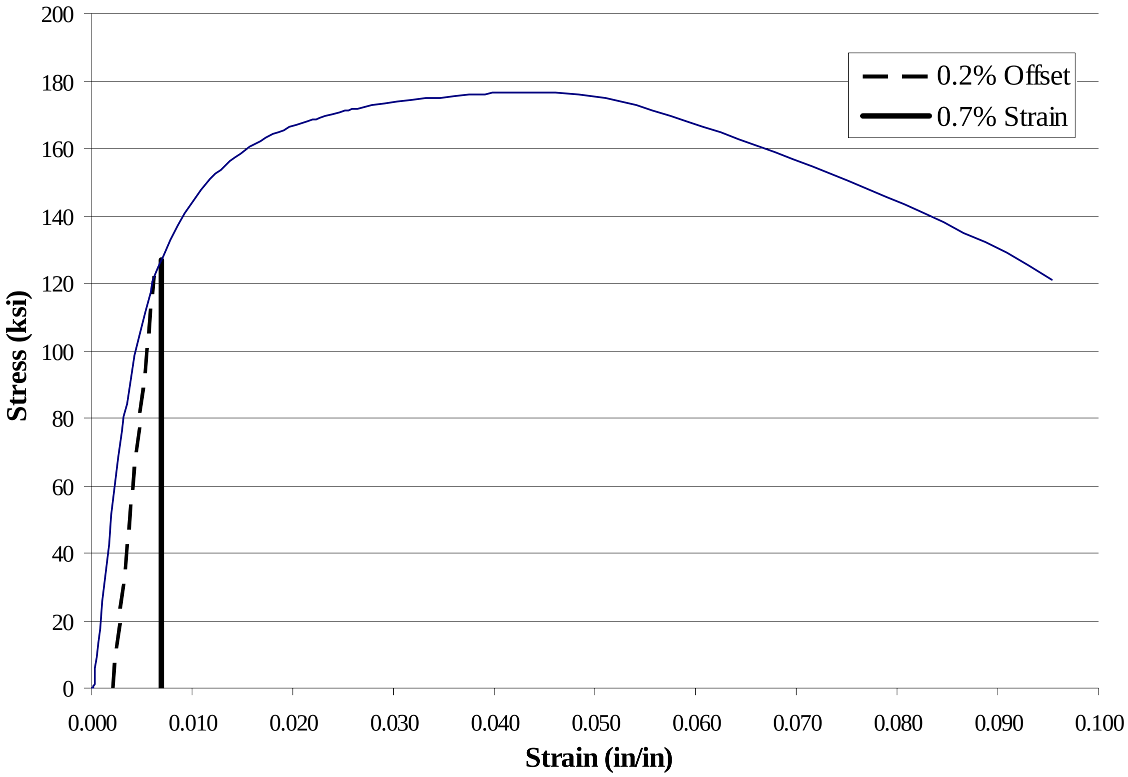


Figure 87: Stress-Strain Graph for MMFX Steel Tension Test 2 (Extensometer Setup)

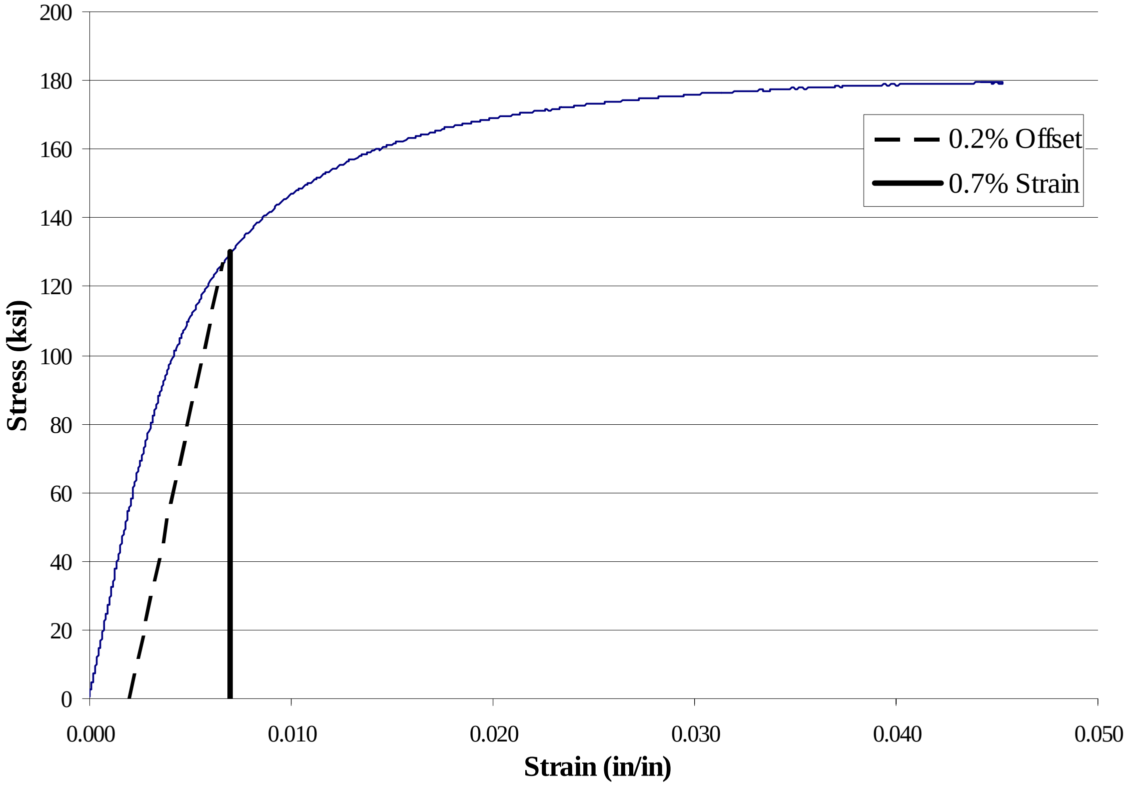


Figure 88: Stress-Strain Graph for MMFX Steel Tension Test 3 (Extensometer Setup)

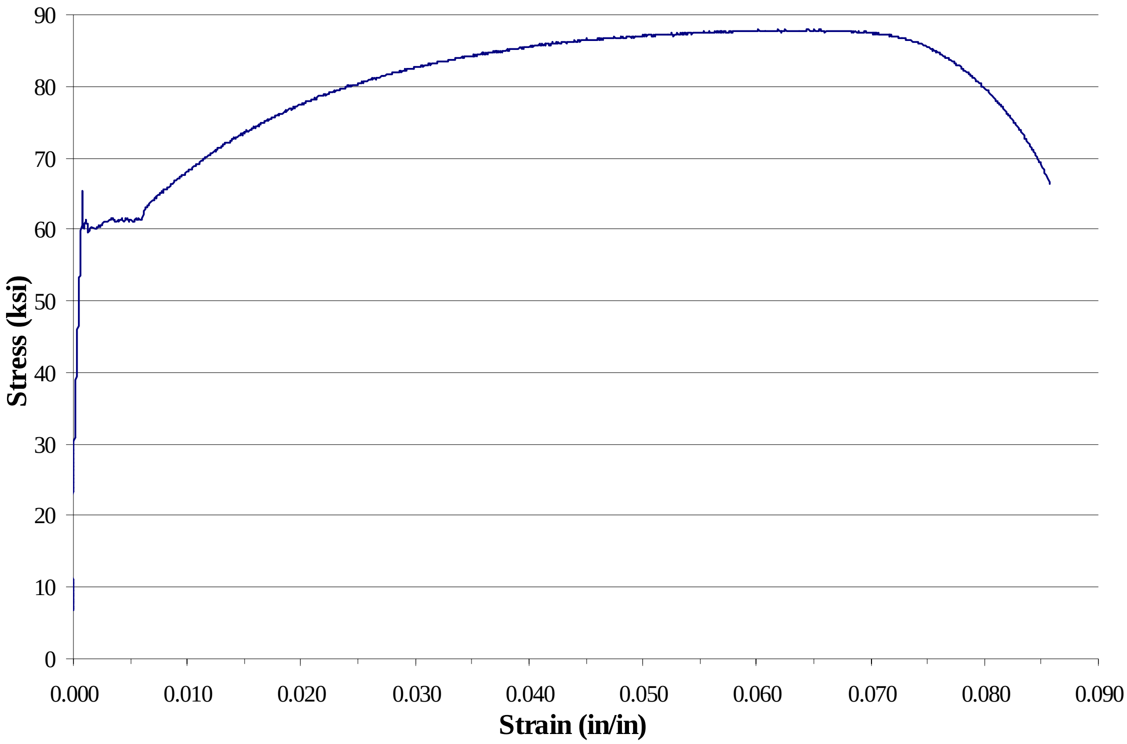


Figure 89: Stress-Strain Graph for Black Steel Tension Test 1 (LVDT Setup)

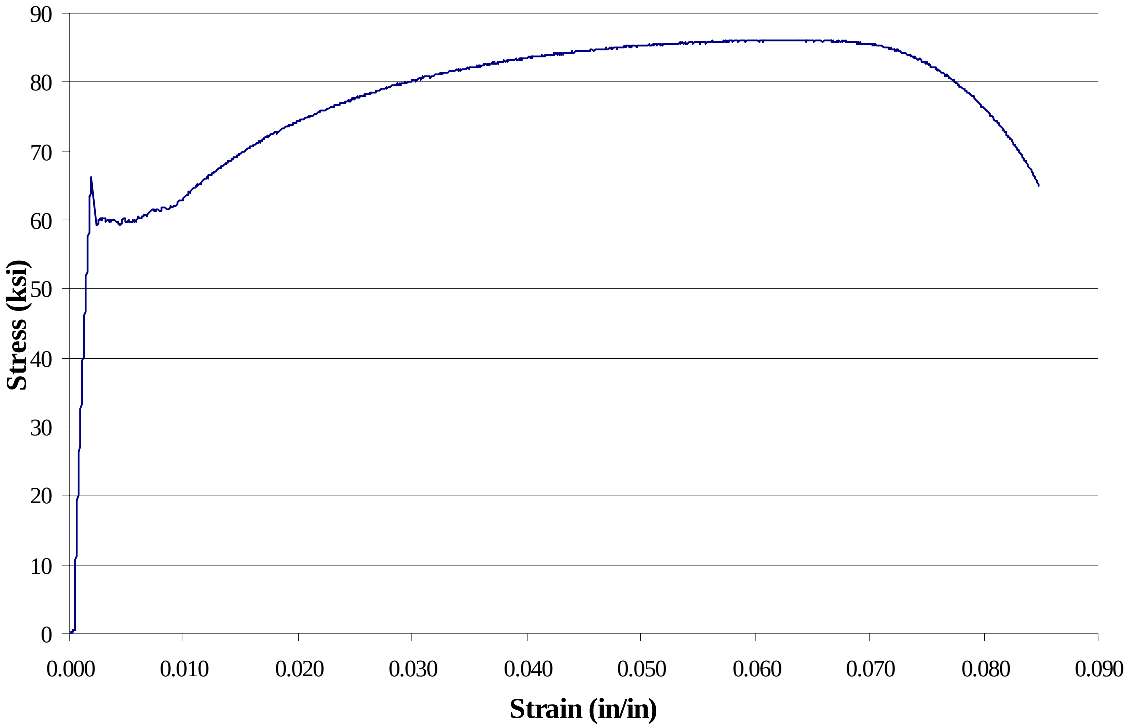


Figure 90: Stress-Strain Graph for Black Steel Tension Test 2 (LVDT Setup)

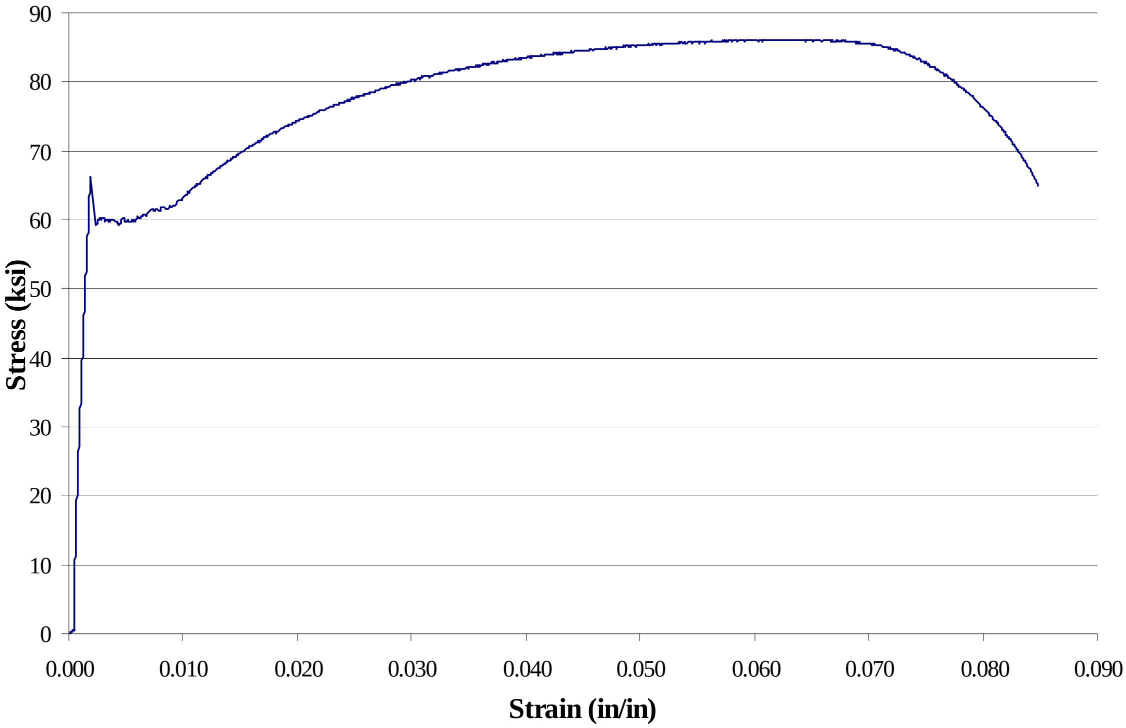


Figure 91: Stress-Strain Graph for Black Steel Tension Test 3 (LVDT Setup)

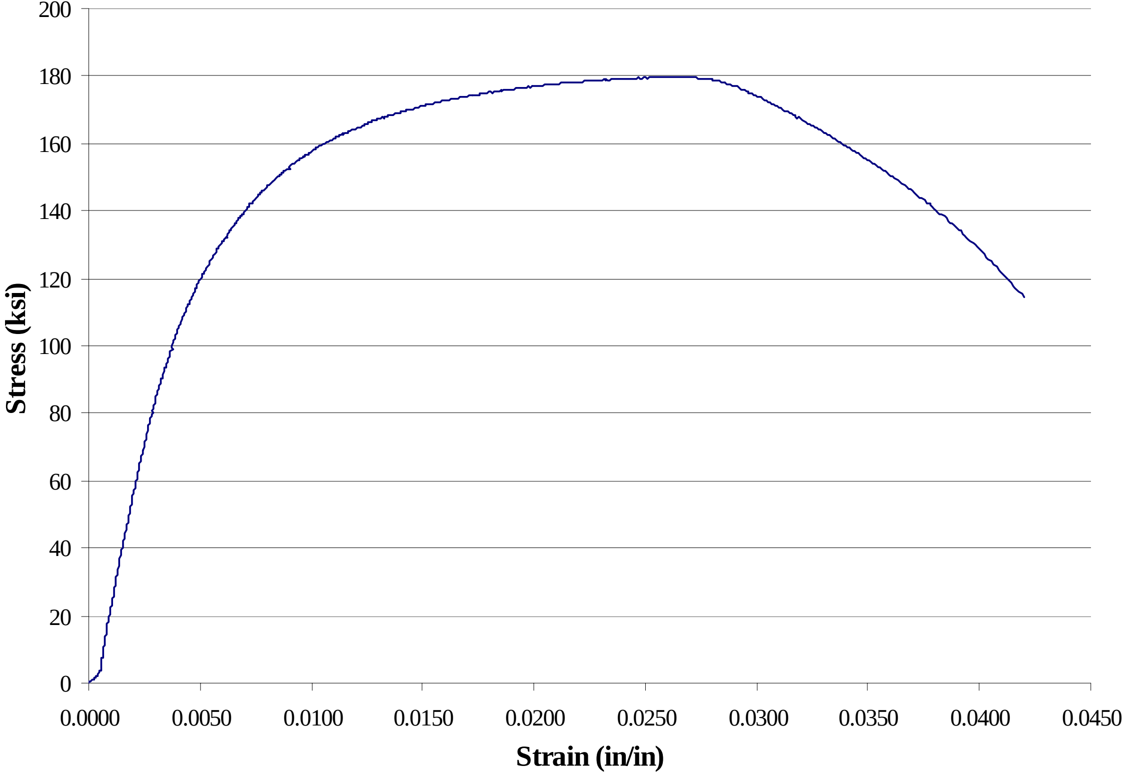


Figure 92: Stress-Strain Graph for MMFX Steel Tension Test 1 (LVDT Setup)

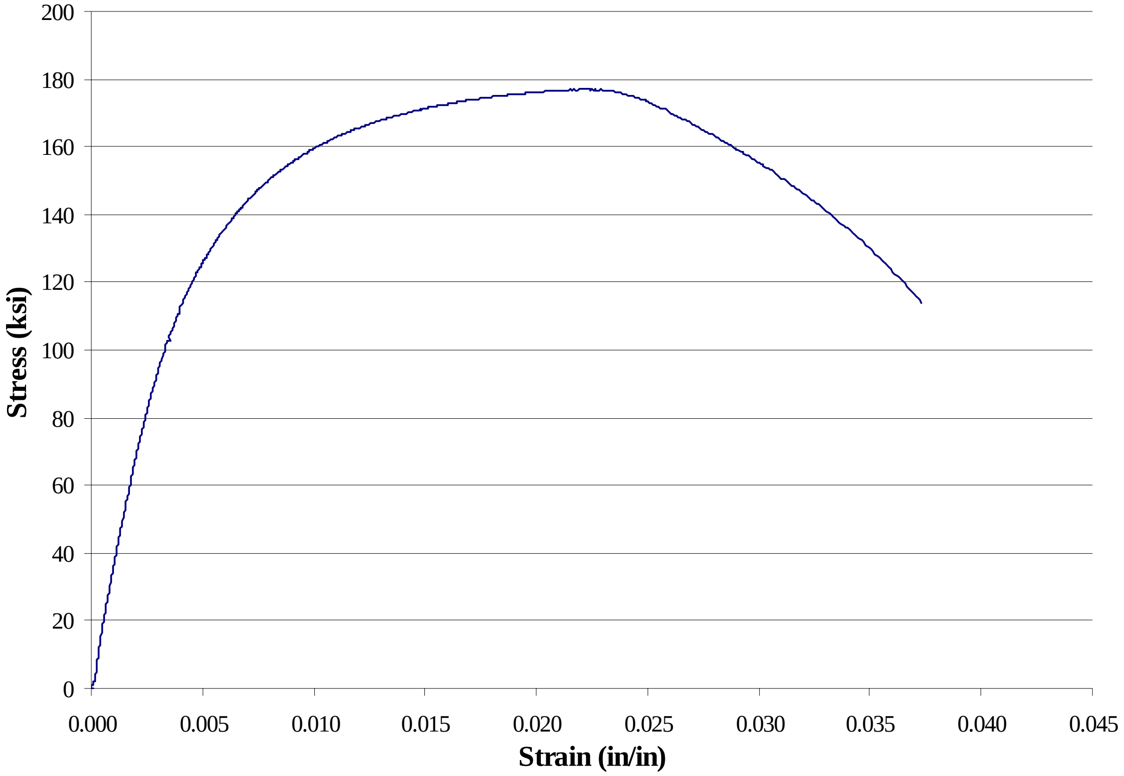


Figure 93: Stress-Strain Graph for MMFX Steel Tension Test 2 (LVDT Setup)

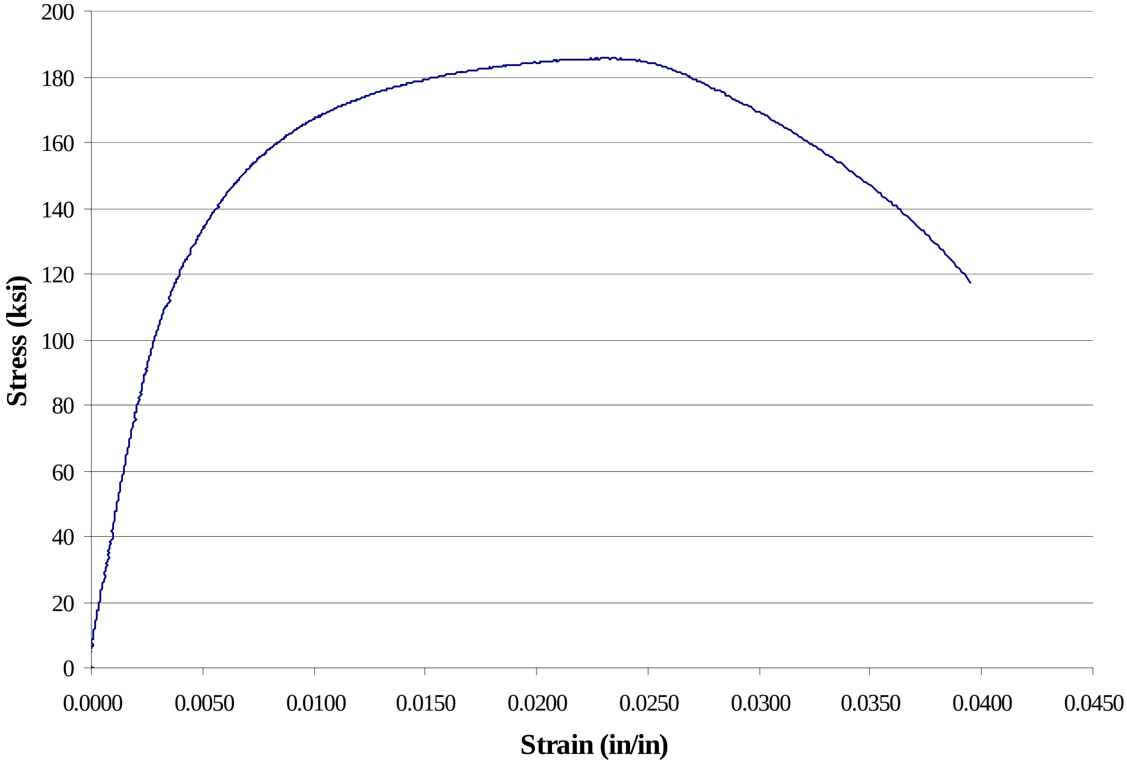


Figure 94: Stress-Strain Graph for MMFX Steel Tension Test 3 (LVDT Setup)

4.3 Results of ASTM C 39/C 39M-01 Compression Testing of Cores

The results of the compression testing done in conformance with ASTM C 39 are shown below in Tables 4.6 and 4.7.

Table 4.6 Results of Compression Testing of Cores with IPANEX from Northbound Bridge on I-35 over Chikaskia River, Kay County, Oklahoma

Core	Failure Load (lb)	L/D	Correction Factor	Corrected Load (lb)	Ultimate Strength (psi)	Failure Type
C4	18950	2.6	1	18,950	3,237	columnar
C6	31350	1.6	0.97	30,410	5,157	cone & split
Note: Both cores contained steel approximately 2.5" from top. Cores contain IPANEX.						

Table 4.7 Results of Compression Testing of Cores without IPANEX from Southbound Bridge on I-35 over Chikaskia River, Kay County, Oklahoma

Core	Failure Load (lb)	L/D	Correction Factor	Corrected Load (lb)	Ultimate Strength (psi)	Failure Type
D4	41260	2.1	1	41,260	6,997	cone & shear
D6	36150	2.2	1	36,150	6,086	cone & split
Note: Core D4 contained reinforcing steel approximately 2.5" from top. Core D6 contained reinforcing steel approximately 3.5" from top. Cores do not contain IPANEX.						

4.4 Results of ASTM C 1202-97 Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

The results of test method C 1202 are shown in Tables 4.8 - 4.11. The total record of each test can be found in Appendix D. NI-0.40-0 and I-0.40-0 are the same mix design as the southbound and northbound bridge decks of the Kay County bridges respectively. The diameter of the samples for batch I-0.40-0 and NI-0.40-0 were 4 in. The diameter of the cores from the bridge deck was 3.75 in. ASTM C 1202 requires a correction factor to be applied for specimens other than 3.75 in. The correction factor is $(3.75/x)^2$, where x is the diameter of the specimen.

Table 4.8 Results of Test Method C 1202 with IPANEX for Cores from Northbound Bridge on I-35 over Chikaskia River, Kay County, Oklahoma

Core	Total Charge Passed (Coulombs)
A4	3152
A6	2683
B4	2158
B6	2741
Average	2683.5
Standard Deviation	407.8
Note: Age at testing was 400 days.	

Table 4.9 Results of Test Method C 1202 for Cores without IPANEX from Southbound Bridge on I-35 over Chikaskia River, Kay County, Oklahoma

Core	Total Charge Passed (Coulombs)
E4	2148
E6	1718
F4	1802
F6	1949
Average	1904.3
Standard Deviation	188.5
Note: Age at testing was 715 days.	

Table 4.10 Results of Test Method C 1202 for NI-0.40-0 (Laboratory Cast)

Sample	Total Charge Passed (Coulombs)
1	1566
2	1594
Average	1580
Standard Deviation	19.8
Note: Age at testing was 126 days.	

Table 4.11 Results of Test Method ASTM C 1202 for I-0.40-0 (Laboratory Cast)

Sample	Total Charge Passed (Coulombs)
1	3860
2	4546
3	3357
4	4057
Average	3955.3
Standard Deviation	492.1
Note: Age at testing was 31 days.	

4.5 Results of ASTM 469 Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression

The modulus of elasticity was measured for two sets of field cast cylinders cast with IPANEX. The group designated G-1 was cast on 1/07/03. The group designated G-2 was cast 1/20/03. The results are shown below in Tables 4.12 and 4.13. The full record of the test is located in Appendix E.

Table 4.12 Measured Modulus of Elasticity for G-1 with IPANEX

Cylinder	Modulus of Elasticity (psi)
1	5,600,000
2	5,600,000
3	5,250,000
Average	5,483,333
Standard Deviation	202,072

Table 4.13 Measured Modulus of Elasticity for G-2 with IPANEX

Cylinder	Modulus of Elasticity (psi)
1	5,567,240
2	5,735,944
3	6,073,353
Average	5,792,179
Standard Deviation	257,700

4.6 Statistical Analysis of Fresh and Hardened Properties of Concrete Used in Bridge Decks over Chikaskia River on I-35 in Kay County, Oklahoma

Tables 4.14 and 4.15 contain the fresh and hardened properties of concrete used in the bridge decks with and without IPANEX. The fresh properties of concrete temperature, slump, air content, and unit weight are shown for each span of each bridge. The 7 and 28 day compressive strength of field cast cylinders from the bridge deck concrete is also shown for each span. These properties were measured by ODOT field technicians. The properties for each batch measured are tabulated in Appendix F.

Table 4.14 Fresh and Hardened Properties for Northbound Bridge Deck Concrete with IPANEX

		Span				
		1	2	3	4	5
Fresh Properties	Date Cast	1/7/03	1/08/03	1/20/03	1/20/03	1/28/03
	Air Temp. (° F)	37	45*	47.5*	56.5*	45*
	Conc. Temp. (° F)	64	70*	64*	66.5*	55*
	Slump (in.)	6.5	6.5*	4.375*	5.5*	3.875*
	Air Cont. (%)	5.5	8.2*	5.5%*	6.9*	6.55*
	Unit Wt. (pcf)	N/A	N/A	146.9*	141.5	146.7*
Hardened Properties	7 Day Compressive Strength (psi)	4789	3348*	4272*	3723*	3628*
	28 Day Compressive Strength (psi)	5588	4431*	5260*	5228*	4748*
* Average of two measurements.						

Table 4.15 Fresh and Hardened Properties for Southbound Bridge Deck Concrete without IPANEX

		Span				
		1	2	3	4	5
Fresh Properties	Date Cast	3/6/02	3/8/02	3/11/02	3/12/02	3/12/02
	Air Temp. (° F)	52.5*	61	53	42.5*	62*
	Conc. Temp. (° F)	56*	65	57	54.5*	65*
	Slump (in.)	7.25*	9.0	8.0	6.125*	5.125*
	Air Cont. (%)	7.5*	6.5	5.7	6.4*	4.75*
	Unit Wt. (pcf)	146.3	146.3	146.3	N/A	150.7
Hardened Properties	7 Day Compressive Strength (psi)	3965*	3238	4403	3341*	3793*
	28 Day Compressive Strength (psi)	5465*	4966	5288	4913*	5192*
* Average of two measurements.						

5. DISCUSSION OF RESULTS

5.1 Discussion of ASTM G 109 Results

ASTM G 109 requires the period of testing to last until the average macrocell current is 10 μA or greater, and at least half the samples show macrocell currents equal to or greater than 10 μA. The test should be continued three more cycles once the macrocell current requirements are met.

At this point in the test only three groups have shown macrocell currents above 10 μA. Those groups are I-0.48-2-B, NI-0.44-5-M, and NI-0.48-5-B. However, the average macrocell current for the three groups has not been above 10 μA for three cycles. So these tests are not yet complete in accordance with ASTM G 109. NI-0.44-5 has only one specimen with a macrocell current above 10 μA, this has occurred within the past 4 weeks. I-0.48-2-B and NI-0.48-5-B have two specimens with a macrocell current above 10 μA. They have been producing measurable macrocell current since the beginning of the test.

I-0.40-5-B has sustained a very low average macrocell current of about 1.0 μA or less since the beginning of testing. One specimen of NI-0.48-5-G showed a macrocell current of 8.6 μA. This may be caused by a scratch or holiday in the epoxy coating. Overall, most specimens are not producing consistent measurable macrocell current or any macrocell current at all.

The total corrosion of most specimens is also zero or very low. This is due to the fact that most specimens are not producing a measurable macrocell current. The average total corrosion of each group is shown in Figure 95.

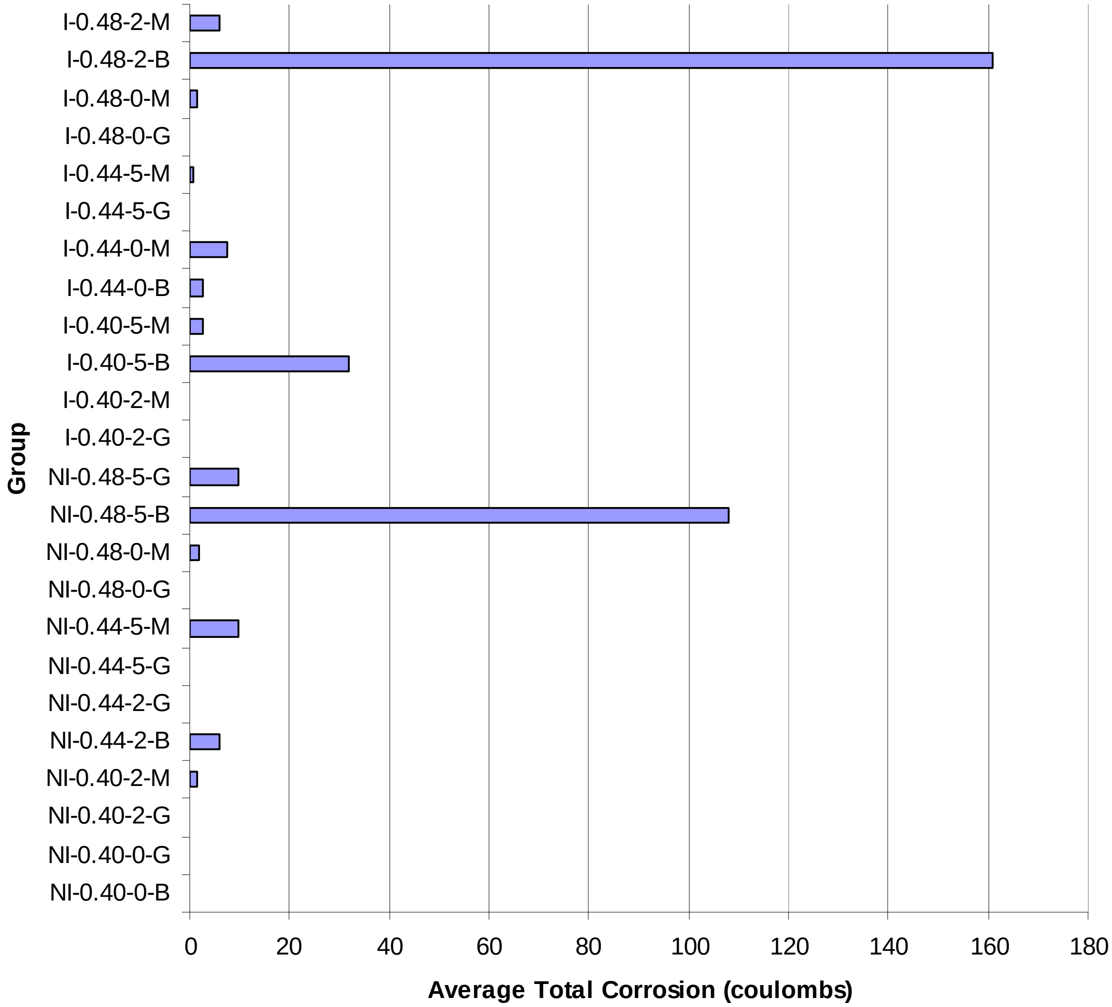


Figure 95: Average Total Corrosion of Each Group in ASTM G 109 Test

Figure 94 shows that there are many groups with measurable corrosion. Two groups dominate the figure. The high average total corrosion of NI-0.48-5-B and I-0.48-2-B is due to the large macrocell currents they are producing. The total corrosion is calculated by integrating the macrocell current over time. Thus, the larger the macrocell current, the more total corrosion calculated.

Specimens with uncoated or “black” steel have the highest average total corrosion. There are five of the six uncoated groups with measurable corrosion. However, two of these groups have very small corrosion values of less than 10 coulombs.

Seven of the nine groups with MMFX steel have measurable corrosion values, but none of the values are larger than 10 coulombs. Most of the corrosion can be contributed to measurable macrocell currents occurring a few isolated times. The current was very low in magnitude and was not sustained.

Only two of the nine groups with epoxy coated steel have measurable corrosion values. The average total corrosion value of 10 coulombs for NI-0.48-5-G is due to 4 instances of a macrocell current measured. The current was not consistently measured. The average total corrosion of the other group, I-0.49-0-G, is less than 1 coulomb.

The majority of the corrosion is occurring in specimens with w/cm of 0.44 and 0.48. In addition the most corrosion is occurring in specimens with chloride values of 2 pcf and 5 pcf. Nine groups with IPANEX have measurable values of corrosion. In comparison, six groups without IPANEX have measurable values of corrosion.

There is a direct correlation between macrocell current and corrosion potential. When the macrocell current increases, the corrosion potential also increases. The opposite is also true. There is one exception to the observation. One specimen of I-0.48-

0-G has shown a potential of greater than 150 mV, with no measured macrocell current. It is not known why this is occurring.

Corrosion potentials have varied significantly in magnitude. The lowest recorded value is 5.8 mV for a specimen in the group NI-0.44-2-G. The highest recorded value is 276.1 mV for a specimen in the group I-0.48-2-B. There is no specific value of corrosion potential at which a macrocell current will be produced. However, a potential around 100 mV seems to be a general rule of thumb. The average corrosion potential for each combination is shown in Figure 96.

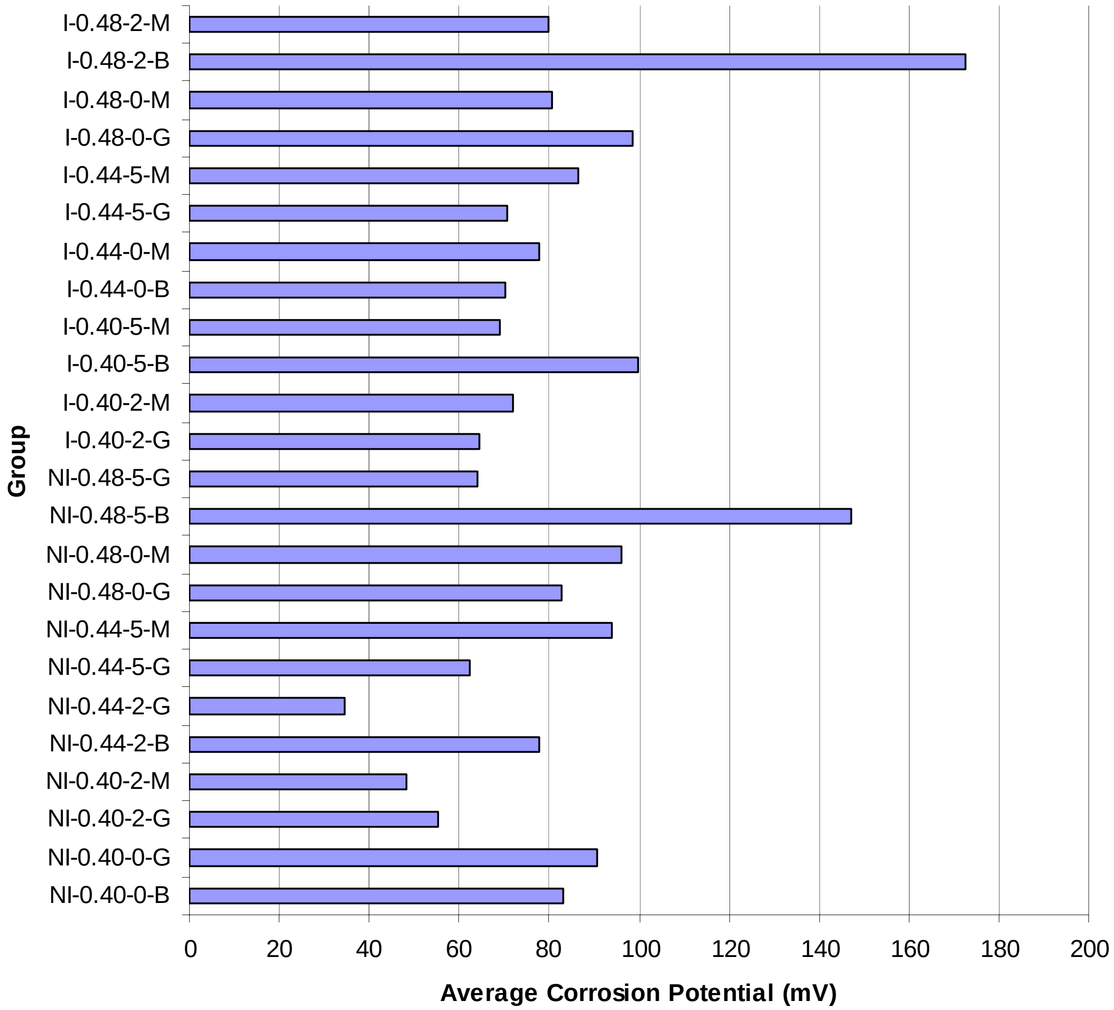


Figure 96: Average Corrosion Potential of Each Combination for ASTM G 109

5.2 Discussion of the Material Properties of MMFX and Grade 60 Reinforcing Bars

The average elastic modulus calculated for the Grade 60 reinforcing bars was 29,216 ksi. The standard deviation was 2,923 for 3 specimens. The average elastic modulus calculated for the MMFX reinforcing bars was 27,921. The standard deviation was 419 ksi. Both of these moduli are close to the accepted value of 29,000 ksi for steel.

The average yield strength of MMFX steel is almost twice that of conventional Grade 60 reinforcing. The average yield strength is 124.7 ksi for the 0.2% offset method, and 129.0 ksi for the 0.7% strain method. In comparison, the average yield strength for the Grade 60 bars is 63.9 ksi.

The average yield strain for the 0.2% offset method is 0.00647 in/in for MMFX steel. The average yield strain for conventional Grade 60 reinforcing is 0.00228. This is less than half of MMFX steel. The average elongation at failure for Grade 60 steel was 8.6%. The average elongation at failure for MMFX steel was 4.0%.

The average 0.2% offset method yield strength of 124.7 ksi agrees with the yield strengths found by independent laboratories and reported by MMFX Steel Corporation (MMFX Steel Corporation, 2001). The average ultimate strength of 178.1 agree with other reports of the ultimate strength of MMFX steel [(Darwin et al., 2002), (El-Hacha and Rizkalla, 2002), (MMFX Steel Corporation, 2001)]. The strain at the 0.2% offset and the ultimate strain are very close to the values of those strains reported by North Carolina State University (El-Hacha and Rizkalla, 2002).

MMFX steel met all of the minimum requirements as set by MMFX Steel Corporation. All samples surpassed the minimum yield strength of 100 ksi, the minimum ultimate strength of 150 ksi, and the minimum strength of 80 ksi at a strain of 0.0035.

MMFX steel meets the minimum tensile requirements of Grade 60 reinforcing in conformance with ASTM A 615. ASTM A 615 requires a minimum tensile strength of 90 ksi. A 615 also requires the stress at a strain of 0.5% to be a minimum of 60 ksi when there is no defined yield point. A 615 requires a minimum elongation of 9% in 8 in. for #3 reinforcing bars. Since the elongation was only measured over 4 in., it cannot be stated if MMFX steel meets this requirement. The average elongation of MMFX steel measured over 4 in. was 7.9%.

These results also satisfy the minimum tensile and yield requirements of Grade 75 reinforcing in conformance with ASTM A 615. ASTM A 615 requires a minimum tensile strength of 100 ksi. A 615 also requires the stress at a strain of 0.35% to be a minimum of 75 ksi when there is no defined yield point. Grade 75 reinforcing is not made in a #3 size, so it cannot be said if MMFX steel meets the elongation requirements.

5.3 Discussion of Chloride Permeability of Concrete with and without IPANEX

Cores were taken from two bridge decks, one with IPANEX, the other without. Companion batches for each bridge deck of the same mix design were also made in the laboratory. The charge passed through the concrete is an indicator of the chloride permeability.

The average charge passed for the bridge deck concrete containing IPANEX was 2,683 coulombs. The average charge passed for laboratory batch of this concrete was 3,955 coulombs. In comparison the average charge passed for the bridge deck not containing IPANEX was 1,904 coulombs. The average charge passed for the laboratory batch for this concrete was 1,798 coulombs. The chloride ion permeability according to ASTM C 1202 is shown in Table 5.1.

Table 5.1 Chloride Ion Permeability According to ASTM C 1202

Concrete	Average Coulombs Passed	Chloride Ion Permeability	Age (days)
Bridge Deck with IPANEX	2683.5	Moderate	400
Laboratory batch of bridge deck w/ IPANEX	3955.3	Moderate	31
Bridge deck without IPANEX	1904.3	Low	715
Laboratory batch of bridge deck w/o IPANEX	1580.0	Low	126

All of the concrete had the same w/cm. There is no difference in any of the concrete except for addition of IPANEX. The results indicate that concrete containing IPANEX has less resistance to chloride penetration. This is the opposite effect that IPANEX claims it has.

ASTM C 1202 indicates that sample age could have a significant effect on results. Concrete becomes less permeable with time. The results agree partially agree with this. The youngest concrete has the highest permeability, while the oldest has the second lowest permeability. Bridge deck concrete with IPANEX is 274 days older than the laboratory batch of bridge deck concrete without IPANEX. However, the older concrete has a greater permeability of almost 900 coulombs.

The chemistry of IPANEX could be a reason for the high chloride ion permeability of concrete containing IPANEX. A technical bulletin produced by the manufacturers of IPANEX noted that the chloride ion permeability test was producing similar results to these (IPA, 1998). The bulletin stated that the electro-potential charge of some components of IPANEX may be producing misleading results (IPA, 1998).

5.4 Discussion of the Effect of IPANEX on the Elastic Modulus of Concrete

The modulus of elasticity was measured for two sets of concrete cylinders cast with IPANEX. These sets were denoted G-1 and G-2. The average value for elastic modulus for G-1 is 5,500 ksi. The average value for elastic modulus for G-2 is 5,800 ksi.

The results can be compared to three equations which calculate the elastic modulus based upon compressive strength and/or unit weight. The three equations are:

1. $E_c = 33w_c^{1.5}\sqrt{f'_c}$ (ACI 318R-02)
2. $E_c = 40{,}000\sqrt{f'_c} + 1.0\times10^6$ (Mindess et al. 2003)
3. $E_c = w_c^{2.55} f'^{0.315}_c$ (Mindess et al. 2003)

Equation 1 is from the ACI 318 Building Code. Equation 2 is from ACI Committee 363, High Strength Concrete. Equation 3 is a best fit equation developed by J.E. Cook. The comparison between the prediction of the equation and the measured value is shown in Table 5.2 and 5.3.

Table 5.2 Comparison of Measured Modulus to Equation Prediction for G-1

Measured (psi)	ACI 318 (psi)	ACI 363 (psi)	Cook (psi)
5,483,333	4,560,000	4,200,000	5,133,755

Table 5.3 Comparison of Measured Modulus to Equation Prediction for G-2

Measured (psi)	ACI 318 (psi)	ACI 363 (psi)	Cook (psi)
5,792,179	4,936,345	4,464,102	5,396,755

Both ACI equations underestimate the elastic modulus. The ACI 363 equation gives the largest difference of all three, almost 1,300,000 psi in both cases. The best fit equation by Cook gives a value closest to the average measured modulus. The equation predicts the modulus to within 400,000 psi.

5.5 Discussion of the Effect of IPANEX on Compressive Strength

5.5.1 Compressive Strength of Concrete Cores

Two cores from each bridge deck of the Kay County bridges were tested for compressive strength. The average compressive strength for the cores containing IPANEX is 4,197 psi. The average compressive strength for the cores that do not contain IPANEX is 6,542.

The average compressive strength for the IPANEX cores is considerably low than the cores without IPANEX. This is because one of the cylinders tested for compressive strength had a length to diameter ratio of 2.6. Instead of breaking in compression, the concrete split in tension. This resulted in a much lower value of compressive strength. It should not be considered when evaluating compressive strength.

The compressive strength of the other core containing IPANEX was 5,157 psi. This is interesting considering the 28 day compressive strength of field cast cylinders from this span of the deck. The average of the six cylinders broken for the 28 day compression tests is 5,260 psi. Only two cylinders have values less than 5,157 psi.

The average 28 day compressive strength of the field cast cylinders from the span of the deck not containing IPANEX is 5,288 psi. This is acceptable when compared to the average compressive strength of the cores from the same span of the deck. The strength gain of the concrete was 1,250 psi over almost two years.

5.5.2 Compressive Strength of Field Cast Cylinders

Field records were obtained from the ODOT for the two bridges in Kay County. The 7 and 28 day compressive strength for the bridge deck concrete was analyzed to compare differences, if any.

The results show that the average compressive strengths are slightly lower concrete containing IPANEX than the same concrete without IPANEX. The 7 day average compressive strength for non-IPANEX concrete is 112 psi higher than IPANEX concrete. The 28 day average compressive strength for non-IPANEX concrete is 213 psi higher than IPANEX concrete. This equates to approximately a 4% difference.

5.6 Discussion of the Effect of IPANEX on Fresh Properties

The fresh properties for the bridge deck concrete were also analyzed from ODOT field records for the Kay County bridges. The fresh properties are of slump, air content, and unit weight.

The average slump is slightly lower for IPANEX concrete. The average slump for IPANEX concrete was 5.2 in. compared to an average slump of 6.5 in. for non-IPANEX concrete.

The average air content is slightly higher for IPANEX concrete. The average air content for IPANEX concrete was 6.6% compared to 5.9% for non-IPANEX concrete.

The average unit weight is lower for IPANEX concrete. The average unit weight for IPANEX concrete was 145.7 pcf compared to 148.1 pcf for non-IPANEX concrete.

Overall these differences are small. These differences do not greatly affect the way IPANEX concrete can be used.

6. CONCLUSIONS

The conclusions expressed below are done with respect to the objectives of the experimental program in Section 3.1.

1. *Comparison between MMFX and epoxy coated steel in the ability to form macrocells by testing in conformance with ASTM G 109.*

Based on the data collected so far MMFX steel has formed more macrocells than epoxy coated steel. The average total corrosion is greater for MMFX specimens than epoxy coated specimens. Also MMFX steel has less average total corrosion than uncoated steel. Uncoated steel has the highest corrosion of all steel. Its corrosion performance is the worst based upon the results collected so far.

2. *Evaluation of IPANEX's ability to mitigate or diminish macrocell corrosion by testing in conformance with ASTM G 109.*

More specimens containing IPANEX have produced measurable macrocell current than specimens not containing IPANEX. There has not been enough measurable corrosion to discern the effect of IPANEX.

3. *Compare differences in the material properties of MMFX steel and Grade 60 steel.*

MMFX has yield and ultimate strengths twice that of normal Grade 60 reinforcing bars. The elastic modulus is the same as normal steel, 29,000 ksi. MMFX is more brittle than Grade 60 steel, with elongations at failure less than half of Grade 60.

4. *Evaluation of IPANEX's affect on chloride permeability of concrete in conformance with ASTM C 1202.*

The results of ASTM test method C 1202 show that IPANEX causes concrete to have higher chloride permeability. The age of the concrete appears be having some effect on the permeability. Therefore, it cannot be stated what effect IPANEX has on chloride permeability of concrete.

5. *Comparison of fresh and hardened properties of concrete made with and without IPANEX.*

The measured elastic modulus of concrete containing IPANEX is higher than predicted. IPANEX results in slightly lower compressive strengths. The difference is only 100 – 200 psi. There are slight differences in fresh properties of slump, air content, and unit weight for IPANEX and non-IPANEX concrete.

The objectives of the research are to determine what effects IPANEX and MMFX steel will have on bridge deck durability. Once this is known a recommendation is to be made to the ODOT.

Corrosion testing of specimens with MMFX steel and IPANEX have not progressed long enough for any conclusions to be made with respect to the effect of these materials on corrosion. The corrosion testing has only lasted 6 months. ASTM G 109 corrosion testing should continue until the ASTM requirements have been met to stop the test.

The trends of corrosion measured so far are consistent with the two previously mentioned research studies of MMFX steel (Darwin et al. 2002) (Clemena, 2003). In both of those studies the corrosion performance off MMFX steel was superior to uncoated steel. The data collected from ASTM G 109 so far agree with these two studies. There is not enough data to conclude if MMFX's corrosion performance will be worse than ECR's.

The material properties of MMFX steel are quite different from conventional reinforcing. The effect of increased yield strength of the reinforcing bars on the design of bridge decks should be evaluated.

The differences in fresh and hardened concrete properties caused by IPANEX appear to be small. The effect of IPANEX on chloride permeability is something that should be investigated more. When the G 109 test is completed, the effect of IPANEX on corrosion in the G 109 specimens should be compared to the results of the ASTM C 1202 test.

Therefore, it is the conclusion of this thesis that the effects MMFX and IPANEX have on bridge deck durability cannot be determined at this time. Also no recommendations can be made to the ODOT on the use of MMFX steel and the admixture IPANEX.

7. REFERENCES

American Concrete Institute (ACI). (2002) *Building Code Requirements for Structural Concrete, ACI 318-02.* Farmington Hills, Michigan.

American Concrete Institute (ACI). (1999) *Hot Weather Concreting, ACI 350R-99.* Farmington Hills, Michigan.

ASTM International (2003). *Annual Book of ASTM Standards, Volumes 01.04, 03.02, 04.02*. West Conshohocken, Pennsylvania.

Babaei, K. and Hawkins, N.M. (1987). "Evaluation of Bridge Deck Protective Strategies." *National Cooperative Highway Research Program Report 297,* Transportation Research Board.

Borgard, B., Warren, C., Somayaji, S., and Heidersbach R. (1989). "Correlation Between Corrosion of Reinforcing Steel and Voids and Cracks in Concrete Structures." *Transportation Research Record,* Transportation Research Board, No. 1211, pp. 1-9.

"Bridges on the Rise." (2002). *Engineering News Record*, Vol. 248, No. 3 (Jan. 28), pp. B1-B7, McGraw Hill Companies, New York, N.Y.

Clear K. C. (1974). "Time to Corrosion of Reinforcing Steel in Concrete Slabs." *Transportation Research Record,* Transportation Research Board, No. 500, pp.16-24.

Clemena, G.G. (2003). "Investigation of the Resistance of Several New Metallic Reinforcing Bars to Chloride-Induced Corrosion in Concrete." *Interim Report VTRC 04-R7,* Virginia Transportation Research Council.

Crumpton, C.F., Bukovatz, J.E. (1974). "Corrosion and Kansas Bridges." *Transportation Research Record,* Transportation Research Board, No. 500, pp. 25-31.

Darwin, D., Browning, J., Nguyen T.V., and Locke C. (2002). "Mechanical and Corrosion Properties of a High-Strength, High Chromium Reinforcing Steel for Concrete." *Rep. No. SD2001-05-F*, Center for Research, Inc., University of Kansas.

NCHRP (1979). "Durability of Concrete Bridge Decks." *National Cooperative Highway Research Program Synthesis of Highway Practice 57*, Transportation Research Board.

El-Hacha, R. and Rizkalla S. (2002). "Fundamental Material Properties of MMFX Steel Rebars." *NCSU-CFL Rep. No. 02-04*, Constructed Facilities Laboratory, North Carolina State University.

Enright, M. P. and Frangopol, D. M. (2000). "Survey and Evaluation of Damaged Concrete Bridges." *J. of Bridge Eng.*, ASCE, Vol. 5, No. 1, pp. 31-38.

Hasan, H.O., Ramirez, J.A., and Cleary, D.B. (1995). "Field Evaluation of Concrete Bridge Decks Reinforced with Epoxy-Coated Steel in Indiana." *Transportation Research Record*, Transportation Research Board, No. 1476, pp. 155-161.

IPA Systems Inc. (1998). "IPA Technical Bulletin No. 6." Philadelphia, Pennsylvania.

Mindess, S., Young, J.F., and Darwin, D. (2003). "Concrete", Second Edition, Pearson Education, Upper Saddle River, New Jersey.

"MMFX Material Product Specification." http://www.mmfxsteel.com/technical_resources/mmfx_material_product_specificat.htm (Mar. 5, 2004).

"Technology Overview." http://www.mmfxsteel.com/technologies/Default2.asp (Mar. 5, 2004).

MMFX Steel Corporation (2001). "MMFX Steel Testing Program." Charlotte, North Carolina.

"National Bridge Inventory." http://www.fhwa.dot.gov/bridge/nbi.htm, Federal Highway Administration. (Feb. 5, 2004).

Phillips, M.V., Ramey, G.E., and Pittman, D.W. (1997). "Bridge Deck Construction Using Type K Cement." *J. of Bridge Eng.*, ASCE, Vol. 2, No. 4, pp. 176-182.

Pyc, W., Weyers R.E., Weyers, R.M., Mokarem, D., Zemajtis, J., and Sprinkel, M.M., Dillard, J.G. (2000). *Rep. VTRC 00-R16*, Department of Civil and Environmental Engineering, Department of Chemical Engineering, Virginia Polytechnic Institute and State University.

Ramey, G.E., Stallings, J.M., and Oliver, R.S. (1999). "Cracking Damage/Deterioration and Rehabilitation Considerations of Some Birmingham, Alabama, Interstate Bridge Decks." *Transportation Research Record*, Transportation Research Board, No. 1668, pp. 33-41.

Russell, B.W., Bowen, C.M., and Painter, S. (2004). "Evaluating the State of the State's Bridges." Dep. Of Civil and Environmental Engineering, Oklahoma State University, Oklahoma Department of Transportation.

Scannell, W.T. and Clear K.C. (1990). "Long-Term Outdoor Exposure Evaluation of Concrete Slabs Containing Epoxy-Coated Reinforcing Steel." *Transportation Research Record*, Transportation Research Board, No. 1284, pp. 70-78.

Schmitt, T.R. and Darwin, D. (1999). "Effect of Material Properties on Cracking in Bridge Decks." *J. of Bridge Eng.*, ASCE, Vol. 4, No. 1, pp. 8-13.

Weyers R.E., Pyc, W., Zemajtis, J., Liu, Y., Mokarem, D., and Sprinkel, M.M. (1997). "Field Investigation of Corrosion-Protection Performance of Bridge Decks Constructed with Epoxy-Coated Reinforcing Steel in Virginia." *Transportation Research Record*, Transportation Research Board, No. 1597, pp. 82-90.

APPENDIX A – MIX DESIGNS & FRESH AND HARDENED PROPERTIES FOR ASTM G 109

Table A.1 Mix Design and Fresh Properties for I-0.40-2

DATE	26-Aug-03	TIME	11:30AM	
MIXTURE	**I-0.40-2**		W/C	0.49
			W/Cm	0.40
BATCH SIZE	2.25	cubic feet		

MIX PROPORTIONS							
MATERIALS		SSD AGGREGATES (PCY)	ADJUSTED FOR AGGREGATE MOISTURE (PCY)	BATCH QUANTITIES			
CEMENT		559.0	559.0	46.6	lb	21130.2	gm
FLYASH		133.0	133.0	11.1	lb	5027.4	gm
COARSE AGGREGATES		1710.0	1703.4	142.0	lb	64389.1	gm
FINE AGGREGATES		1272.0	1266.7	105.6	lb	47880.7	gm
WATER		275.0	286.9	23.9	lb	10844.8	gm
WATER ADJUSTED FOR ADMIXTURES						10519.0	gm
ADMIXTURES	AE	5.6	5.6	0.5	fl oz	13.9	ml
	IPNEX	77.1	77.1	6.4	fl oz	190.3	ml
	Cacl$_2$	2.0	PCY	0.5	lb	236.3	gm

FRESH CONCRETE PROPERTIES

	ASTM		
SLUMP	C 143	7.25	in
CONCRETE TEMP.	C 1064	87	F
AIR TEMP.		82	F
RELATIVE HUMIDITY		47	%
UNIT WEIGHT	C 138	144.00	pcf
BUCKET WEIGHT		8.00	lb
BUCKET + CONCRETE		43.75	lb
CONCETE WEIGHT		35.75	lb
VOLUME OF BUCKET		0.25	cf
AIR CONTENT	C231	5.00	%

MOISTURE CONTENT

	MC	AC
COARSE	0.113%	0.50%
FINE	0.080%	0.50%

MC MOISTURE CONTENT

AC ABSORPTION CONTENT

Table A.2 Hardened Properties of I-0.40-2

DATE	26-Aug-03	TIME	11:30AM
MIXTURE		**I-0.40-2**	

1-DAY STRENGTHS			27-Aug-2003	11:30AM
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	20,233	1,610	shear	
2	21,807	1,735	shear	
3	23,155	1,843	shear	
AVG	21,732	1,730		

9-DAY STRENGTHS			2-Sep-2003	11:30AM
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	52,600	4,186	shear	
2	53,280	4,240	shear	
3	50,000	3,979	shear	
AVG	51,960	4,130		

28-DAY STRENGTHS			23-Sep-2003	11:30AM
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	62,270	4,955	shear	
2	64,750	5,153	shear	
3	65,870	5,242	shear	
AVG	64,297	5,120		

Table A.3 Mix Design and Fresh Properties of I-0.40-5

DATE	6-Aug-03	TIME	2:30 PM
MIXTURE	**I-0.40-5**	W/C	0.49
		W/Cm	0.40
BATCH SIZE	2.25 cubic feet		

MIX PROPORTIONS

MATERIALS		SSD AGGREGATES (PCY)	ADJUSTED FOR AGGREGATE MOISTURE (PCY)	BATCH QUANTITIES	
CEMENT		559.0	559.0	46.6 lb	21130.2 gm
FLYASH		133.0	133.0	11.1 lb	5027.4 gm
COARSE AGGREGATES		1710.0	1703.4	141.9 lb	64388.3 gm
FINE AGGREGATES		1306.0	1300.4	108.4 lb	49155.6 gm
WATER		275.0	287.2	23.9 lb	10855.9 gm
WATER ADJUSTED FOR ADMIXTURES					10560.8 gm
ADMIXTURES	AE	6.2	6.2	0.5 fl oz	15.4 ml
	IPNEX	77.1	77.1	6.4 fl oz	190.3 ml
	Cacl2	5.0	PCY	0.4 lb	189.0 gm

FRESH CONCRETE PROPERTIES

	ASTM		
SLUMP	C 143	6.5	in
CONCRETE TEMP.	C 1064	87	F
AIR TEMP.		84.5	F
RELATIVE HUMIDITY		62	%
UNIT WEIGHT	C 138	145	pcf
BUCKET WEIGHT		8.00	lb
BUCKET + CONCRETE		44.00	lb
CONCETE WEIGHT		36.00	lb
VOLUME OF BUCKET		0.248	cf
AIR CONTENT	C231	4.10	%

MOISTURE CONTENT

	MC	AC
COARSE	0.570%	0.96%
FINE	0.070%	0.50%

MC - MOISTURE CONTENT

AC - ABSORPTION CONTENT

Table A.4 Hardened Properties of I-0.40-5

DATE	6-Aug-03	TIME	2:30 PM
MIXTURE	**I-0.40-5**		

1-DAY STRENGTHS			7-Aug-2003	2:30 PM	
	COMPRESSION				NOTES:
TEST	lb	psi	FAILURE TYPE		
1	27,500	2,188	Shear		
2	28,000	2,228	Shear		
3	32,000	2,546	Shear		
AVG	29,167	2,320			

7-DAY STRENGTHS			13-Aug-2003	2:30 PM	
	COMPRESSION				NOTES:
TEST	lb	psi	FAILURE TYPE		
1	56,750	4,516	Shear		
2	57,000	4,536	Shear		
3	58,250	4,635	Shear		
AVG	57,333	4,560			

28-DAY STRENGTHS			3-Sep-2003	2:30 PM	
	COMPRESSION				NOTES:
TEST	lb	psi	FAILURE TYPE		
1	70,000	5,570	Shear		
2	71,500	5,690	Shear		
3	70,000	5,570	Shear		
AVG	70,500	5,610			

Table A.5 Mix Design and Fresh Properties of I-0.44-0

DATE	4-Aug-03	TIME	2:45 PM
MIXTURE	**I-0.44-0**	W/C	0.54
		W/Cm	0.44
BATCH SIZE	2.50 cubic feet		

MIX PROPORTIONS

MATERIALS		SSD AGGREGATES (PCY)	ADJUSTED FOR AGGREGATE MOISTURE (PCY)	BATCH QUANTITIES			
CEMENT		506.0	506.0	46.9	lb	21252.0	gm
FLYASH		119.0	119.0	11.0	lb	4998.0	gm
COARSE AGGREGATES		1710.0	1715.8	158.9	lb	72061.9	gm
FINE AGGREGATES		1262.0	1256.6	116.4	lb	52777.2	gm
WATER		275.0	274.6	25.4	lb	11534.9	gm
WATER ADJUSTED FOR ADMIXTURES						11367.4	gm
ADMIXTURES	AE	5.6	5.6	0.5	fl oz	15.4	ml
	IPNEX	69.8	69.8	6.5	fl oz	191.4	ml
	Cacl2	0.0	PCY	0.0	lb	0.0	gm

FRESH CONCRETE PROPERTIES

	ASTM		
SLUMP	C 143	8.25	in
CONCRETE TEMP.	C 1064	83	F
AIR TEMP.		79	F
RELATIVE HUMIDITY		86	%
UNIT WEIGHT	C 138	144	pcf
BUCKET WEIGHT		8.00	lb
BUCKET + CONCRETE		43.75	lb
CONCETE WEIGHT		35.75	lb
VOLUME OF BUCKET		0.248	cf
AIR CONTENT	C231	5.50	%

MOISTURE CONTENT

	MC	AC
COARSE	1.300%	0.96%
FINE	0.070%	0.50%

MC MOISTURE CONTENT

AC ABSORPTION CONTENT

Table A.6 Hardened Properties of I-0.44-0

DATE	4-Aug-03	TIME	2:45 PM
MIXTURE	**I-0.44-0**		

1-DAY STRENGTHS			5-Aug-2003	2:45 PM
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	17,500	1,393	Shear	
2	17,000	1,353	Shear	
3	17,250	1,373	Shear	
AVG	17,250	1,370		

7-DAY STRENGTHS			11-Aug-2003	2:45 PM
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	45,000	3,581	Shear	
2	47,500	3,780	Shear	
3	48,750	3,879	Shear	
AVG	47,083	3,750		

28-DAY STRENGTHS			1-Sep-2003	2:45 PM
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	63,050	5,017	Shear	
2	58,900	4,687	Shear	
3	58,225	4,633	Shear	
AVG	60,058	4,780		

Table A.7 Mix design and fresh properties of I-0.44-5

DATE	28-Aug-03	TIME	2:10PM
MIXTURE	**I-0.44-5**	W/C	0.54
		W/Cm	0.44
BATCH SIZE	2.25 cubic feet		

MIX PROPORTIONS							
MATERIALS		SSD AGGREGATES (PCY)	ADJUSTED FOR AGGREGATE MOISTURE (PCY)	BATCH QUANTITIES			
CEMENT		506.0	506.0	42.2	lb	19126.8	gm
FLYASH		119.0	119.0	9.9	lb	4498.2	gm
COARSE AGGREGATES		1710.0	1703.7	142.0	lb	64398.1	gm
FINE AGGREGATES		1262.0	1256.8	104.7	lb	47506.1	gm
WATER		275.0	286.6	23.9	lb	10832.4	gm
WATER ADJUSTED FOR ADMIXTURES						10280.0	gm
ADMIXTURES	AE	5.6	5.6	0.5	fl oz	13.9	ml
	IPNEX	69.8	69.8	5.8	fl oz	172.2	ml
	Cacl2	5.0	PCY	1.3	lb	590.6	gm

FRESH CONCRETE PROPERTIES

	ASTM		
SLUMP	C 143	5.50	in
CONCRETE TEMP.	C 1064	87	F
AIR TEMP.		77	F
RELATIVE HUMIDITY		56	%
UNIT WEIGHT	C 138	145.00	pcf
BUCKET WEIGHT		8.00	lb
BUCKET + CONCRETE		44.00	lb
CONCETE WEIGHT		36.00	lb
VOLUME OF BUCKET		0.248	cf
AIR CONTENT	C231	4.20	%

MOISTURE CONTENT

	MC	AC
COARSE	0.127%	0.50%
FINE	0.084%	0.50%

MC MOISTURE CONTENT

AC ABSORPTION CONTENT

Table A.8 Hardened concrete properties of I-0.44-5

DATE	28-Aug-03	TIME	2:10PM
MIXTURE		**I-0.44-5**	

1-DAY STRENGTHS			29-Aug-03	2:10PM	
	COMPRESSION				NOTES:
TEST	lb	psi	FAILURE TYPE		
1	33,385	2,657	shear		
2	32,150	2,558	shear		
3	31,800	2,531	shear		
AVG	32,445	2,580			
5-DAY STRENGTHS			2-Sep-03	2:10PM	
	COMPRESSION				NOTES: Performed the tests at 5 days from the batching date
TEST	lb	psi	FAILURE TYPE		
1	61,150	4,866	shear		
2	63,400	5,045	shear		
3	61,150	4,866	shear		
AVG	61,900	4,930			
28-DAY STRENGTHS			25-Sep-03	2:10PM	
	COMPRESSION				NOTES:
TEST	lb	psi	FAILURE TYPE		
1	78,235	6,226	shear		
2	80,260	6,387	shear		
3	78,690	6,262	shear		
AVG	79,062	6,290			

Table A.9 Mix design and fresh properties of I-0.48-0

DATE	19-Aug-03	TIME	12:45 PM
MIXTURE	**I-0.48-0**	W/C	0.59
		W/Cm	0.48
BATCH SIZE	2.25 cubic feet		

MIX PROPORTIONS							
MATERIALS		SSD AGGREGATES (PCY)	ADJUSTED FOR AGGREGATE MOISTURE (PCY)	BATCH QUANTITIES			
CEMENT		464.0	464.0	38.7	lb	17539.2	gm
FLYASH		109.0	109.0	9.1	lb	4120.2	gm
COARSE AGGREGATES		1710.0	1702.9	141.9	lb	64367.9	gm
FINE AGGREGATES		1306.0	1300.2	108.3	lb	49145.8	gm
WATER		275.0	288.0	24.0	lb	10886.2	gm
WATER ADJUSTED FOR ADMIXTURES						10747.9	gm
ADMIXTURES	AE	5.2	5.2	0.4	fl oz	12.7	ml
	IPNEX	64.0	64.0	5.3	fl oz	157.9	ml
	$Cacl_2$	0.0	PCY	0.0	lb	0.0	gm

FRESH CONCRETE PROPERTIES

	ASTM		
SLUMP	C 143	8.00	in
CONCRETE TEMP.	C 1064	87	F
AIR TEMP.		82	F
RELATIVE HUMIDITY		44	%
UNIT WEIGHT	C 138	143	pcf
BUCKET WEIGHT		8.00	lb
BUCKET + CONCRETE		43.50	lb
CONCETE WEIGHT		35.50	lb
VOLUME OF BUCKET		0.248	cf
AIR CONTENT	C231	5.10	%

MOISTURE CONTENT

	MC	AC
COARSE	0.080%	0.50%
FINE	0.050%	0.50%

MC MOISTURE CONTENT

AC ABSORPTION CONTENT

Table A.10 Hardened concrete properties of I-0.48-0

DATE	19-Aug-03	TIME	12:45 PM
MIXTURE	**I-0.48-0**		

1-DAY STRENGTHS			20-Aug-2003	12:45 PM	
	COMPRESSION				NOTES:
TEST	lb	psi	FAILURE TYPE		
1	17,250	1,373	Shear		
2	16,000	1,273	Shear		
3	17,000	1,353	Shear		
AVG	16,750	1,330			

7-DAY STRENGTHS			26-Aug-2003	12:45 PM	
	COMPRESSION				NOTES:
TEST	lb	psi	FAILURE TYPE		
1	47,200	3,756	Shear		
2	69,500	5,531	Shear		
3	48,500	3,860	Shear		
AVG	55,067	4,380			

28-DAY STRENGTHS			16-Sep-2003	12:45 PM	
	COMPRESSION				NOTES:
TEST	lb	psi	FAILURE TYPE		
1	60,050	4,779	Shear		
2	59,400	4,727	Shear		
3	59,400	4,727	Shear		
AVG	59,617	4,740			

Table A.11 Mix design and fresh properties of I-0.48-2

DATE 5-Aug-03 TIME 12:55 PM

MIXTURE	**I-0.48-2**	W/C	0.59
		W/Cm	0.48
BATCH SIZE	2.30 cubic feet		

MIX PROPORTIONS

MATERIALS		SSD AGGREGATES (PCY)	ADJUSTED FOR AGGREGATE MOISTURE (PCY)	BATCH QUANTITIES	
CEMENT		464.0	464.0	39.5 lb	17929.0 gm
FLYASH		109.0	109.0	9.3 lb	4211.8 gm
COARSE AGGREGATES		1710.0	1708.1	145.5 lb	66002.4 gm
FINE AGGREGATES		1306.0	1300.4	110.8 lb	50247.9 gm
WATER		275.0	282.5	24.1 lb	10913.9 gm
WATER ADJUSTED FOR ADMIXTURES					10772.6 gm
ADMIXTURES	AE	5.2	5.2	0.4 fl oz	13.0 ml
	IPNEX	64.0	64.0	5.5 fl oz	161.5 ml
	Cacl2	2.0	PCY	0.2 lb	77.3 gm

FRESH CONCRETE PROPERTIES

	ASTM	
SLUMP	C 143	8.50 in
CONCRETE TEMP.	C 1064	84 F
AIR TEMP.		82 F
RELATIVE HUMIDITY		72 %
UNIT WEIGHT	C 138	145 pcf
BUCKET WEIGHT		8.00 lb
BUCKET + CONCRETE		44.00 lb
CONCETE WEIGHT		36.00 lb
VOLUME OF BUCKET		0.248 cf
AIR CONTENT	C231	4.40 %

MOISTURE CONTENT

	MC	AC
COARSE	0.850%	0.96%
FINE	0.070%	0.50%

MC MOISTURE CONTENT

AC ABSORPTION CONTENT

Table A.12 Hardened concrete properties of I-0.48-2

DATE	5-Aug-03	TIME	12:55 PM
MIXTURE	**I-0.48-2**		

1-DAY STRENGTHS			6-Aug-2003	12:55 PM
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	20,750	1,651	Cone and Split	
2	21,250	1,691	Shear	
3	19,500	1,552	Cone and Split	
AVG	20,500	1,630		

7-DAY STRENGTHS			12-Aug-2003	12:55 PM
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	47,250	3,760	Shear	
2	50,000	3,979	Shear	
3	47,500	3,780	Shear	
AVG	48,250	3,840		

28-DAY STRENGTHS			2-Sep-2003	12:55 PM
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	62,950	5,009	Shear	
2	61,150	4,866	Shear	
3	59,575	4,741	Shear	
AVG	61,225	4,870		

Table A.13 Mix design and fresh properties of NI-0.40-0

DATE	21-Aug-03	TIME	11:30AM		
MIXTURE	**NI-0.40-0**			W/C	0.49
				W/Cm	0.40
BATCH SIZE	2.25	cubic feet			

MIX PROPORTIONS

MATERIALS		SSD AGGREGATES (PCY)	ADJUSTED FOR AGGREGATE MOISTURE (PCY)	BATCH QUANTITIES			
CEMENT		559.0	559.0	46.6	lb	21130.2	gm
FLYASH		133.0	133.0	11.1	lb	5027.4	gm
COARSE AGGREGATES		1710.0	1702.7	141.9	lb	64361.4	gm
FINE AGGREGATES		1272.0	1266.6	105.5	lb	47875.9	gm
WATER		275.3	288.1	24.0	lb	10888.6	gm
WATER ADJUSTED FOR ADMIXTURES						10875.7	gm
ADMIXTURES	AE	5.6	5.6	0.5	fl oz	13.9	ml
	IPNEX	0.0	0.0	0.0	fl oz	0.0	ml
	$CaCl_2$	0.0	PCY	0.0	lb	0.0	gm

FRESH CONCRETE PROPERTIES

	ASTM		
SLUMP	C 143	5.25	in
CONCRETE TEMP.	C 1064	87	F
AIR TEMP.		82	F
RELATIVE HUMIDITY		44	%
UNIT WEIGHT	C 138	146.01	pcf
BUCKET WEIGHT		8.00	lb
BUCKET + CONCRETE		44.25	lb
CONCETE WEIGHT		36.25	lb
VOLUME OF BUCKET		0.25	cf
AIR CONTENT	C231	4.00	%

MOISTURE CONTENT

	MC	AC
COARSE	0.070%	0.50%
FINE	0.070%	0.50%

MC MOISTURE CONTENT

AC ABSORPTION CONTENT

Table A.14 Hardened concrete properties of NI-0.40-0

DATE 21-Aug-03 TIME 11:30AM

MIXTURE **NI-0.40-0**

1-DAY STRENGTHS 22-Aug-2003 11:30AM

	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	24,500	1,950	Shear	
2	25,250	2,009	Shear	
3	25,250	2,009	Shear	
AVG	25,000	1,990		

7-DAY STRENGTHS 28-Aug-2003 11:30AM

	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	56,200	4,472	Shear	
2	55,300	4,401	Shear	
3	54,400	4,329	Shear	
AVG	55,300	4,400		

28-DAY STRENGTHS 18-Sep-2003 11:30AM

	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	70,815	5,635	Shear	
2	69,690	5,546	Shear	
3	71,040	5,653	Shear	
AVG	70,515	5,610		

.

Table A.15 Mix design and fresh properties of NI-0.40-2

DATE	9-Sep-03	TIME	11:00AM		
MIXTURE	**NI-0.40-2**			W/C	0.49
				W/Cm	0.40
BATCH SIZE	2.25	cubic feet			

MIX PROPORTIONS

	MATERIALS	SSD AGGREGATES (PCY)	ADJUSTED FOR AGGREGATE MOISTURE (PCY)	BATCH QUANTITIES			
	CEMENT	559.0	559.0	46.6	lb	21130.2	gm
	FLYASH	133.0	133.0	11.1	lb	5027.4	gm
	COARSE AGGREGATES	1710.0	1702.6	141.9	lb	64357.6	gm
	FINE AGGREGATES	1272.0	1266.5	105.5	lb	47872.1	gm
	WATER	275.0	288.0	24.0	lb	10885.0	gm
	WATER ADJUSTED FOR ADMIXTURES					10711.4	gm
ADMIX TURES	AE	5.6	5.6	0.5	fl oz	13.9	ml
	IPNEX	0.0	0.0	0.0	fl oz	0.0	ml
	$CaCl_2$	2.0	PCY	0.5	lb	236.3	gm

FRESH CONCRETE PROPERTIES

	ASTM		
SLUMP	C 143	4.50	in
CONCRETE TEMP.	C 1064	82	F
AIR TEMP.		75	F
RELATIVE HUMIDITY		60	%
UNIT WEIGHT	C 138	147.02	pcf
BUCKET WEIGHT		8.00	lb
BUCKET + CONCRETE		44.50	lb
CONCETE WEIGHT		36.50	lb
VOLUME OF BUCKET		0.25	cf
AIR CONTENT	C231	3.60	%

MOISTURE CONTENT

	MC	AC
COARSE	0.064%	0.50%
FINE	0.062%	0.50%

MC MOISTURE CONTENT

AC ABSORPTION CONTENT

Table A.16 Hardened concrete properties of NI-0.40-2

DATE	9-Sep-03	TIME	11:00AM
MIXTURE	**NI-0.40-2**		

1-DAY STRENGTHS		10-Sep-2003	11:00AM	
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	32,600	2,594	shear	
2	33,725	2,684	shear	
3	32,825	2,612	shear	
AVG	33,050	2,630		

7-DAY STRENGTHS		16-Sep-2003	11:00AM	
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	63,650	5,065	shear	
2	63,430	5,048	shear	
3	65,680	5,227	shear	
AVG	64,253	5,110		

28-DAY STRENGTHS		7-Oct-2003	11:00AM	
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	76,660	6,100	shear	
2	71,490	5,689	shear	
3	75,090	5,975	shear	
AVG	74,413	5,920		

Table A.17 Mix design and fresh properties of NI-0.44-2

DATE 5-Sep-03 TIME 12:20pm

MIXTURE **NI-0.44-2**

W/C 0.54
W/Cm 0.44

BATCH SIZE 2.25 cubic feet

	MIX PROPORTIONS						
	MATERIALS	SSD AGGREGATES (PCY)	ADJUSTED FOR AGGREGATE MOISTURE (PCY)	BATCH QUANTITIES			
	CEMENT	506.0	506.0	42.2	lb	19126.8	gm
	FLYASH	119.0	119.0	9.9	lb	4498.2	gm
	COARSE AGGREGATES	1710.0	1702.8	141.9	lb	64365.3	gm
	FINE AGGREGATES	1262.0	1256.6	104.7	lb	47497.6	gm
	WATER	275.0	287.7	24.0	lb	10873.7	gm
	WATER ADJUSTED FOR ADMIXTURES					10700.1	gm
ADMIXTURES	AE	5.6	5.6	0.5	fl oz	13.9	ml
	IPNEX	0.0	0.0	0.0	fl oz	0.0	ml
	Cacl2	2.0	PCY	0.5	lb	236.3	gm

FRESH CONCRETE PROPERTIES

	ASTM		
SLUMP	C 143	7.00	in
CONCRETE TEMP.	C 1064	80	F
AIR TEMP.		73	F
RELATIVE HUMIDITY		51	%
UNIT WEIGHT	C 138	145.00	pcf
BUCKET WEIGHT		8.00	lb
BUCKET + CONCRETE		44.00	lb
CONCETE WEIGHT		36.00	lb
VOLUME OF BUCKET		0.2483	cf
AIR CONTENT	C231	4.20	%

MOISTURE CONTENT

	MC	AC
COARSE	0.076%	0.50%
FINE	0.066%	0.50%

MC MOISTURE CONTENT

AC ABSORPTION CONTENT

Table A.18 Hardened concrete properties of NI-0.44-2

DATE	5-Sep-03	TIME	12:20pm
MIXTURE		**NI-0.44-2**	

1-DAY STRENGTHS		6-Sep-2003	12:20pm	
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	28,775	2,290	shear	
2	26,550	2,113	shear	
3	28,325	2,254	shear	
AVG	27,883	2,220		

7-DAY STRENGTHS		12-Sep-2003	12:20pm	
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	58,675	4,669	cone and split	
2	62,500	4,974	shear	
3	62,500	4,974	shear	
AVG	61,225	4,870		

28-DAY STRENGTHS		3-Oct-2003	12:20pm	
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	71,715	5,707	shear	
2	73,510	5,850	shear	
3	69,020	5,492	shear	
AVG	71,415	5,680		

Table A.19 Mix design and fresh properties of NI-0.44-5

DATE	9/12/03	TIME	2:00PM
MIXTURE	**NI-0.44-5**	W/C	0.54
		W/Cm	0.44
BATCH SIZE	2.25 cubic feet		

MIX PROPORTIONS

	MATERIALS	SSD AGGREGATES (PCY)	ADJUSTED FOR AGGREGATE MOISTURE (PCY)	BATCH QUANTITIES	
	CEMENT	506.0	506.0	42.2 lb	19126.8 gm
	FLYASH	119.0	119.0	9.9 lb	4498.2 gm
	COARSE AGGREGATES	1710.0	1702.8	141.9 lb	64365.3 gm
	FINE AGGREGATES	1262.0	1256.7	104.7 lb	47501.4 gm
	WATER	275.0	287.6	24.0 lb	10869.9 gm
	WATER ADJUSTED FOR ADMIXTURES				10455.3 gm
ADMIX TURES	AE	5.6	5.6	0.5 fl oz	13.9 ml
	IPNEX	0.0	0.0	0.0 fl oz	0.0 ml
	Cacl2	5.0	PCY	1.3 lb	590.6 gm

FRESH CONCRETE PROPERTIES

	ASTM	
SLUMP	C 143	8.00 in
CONCRETE TEMP.	C 1064	82 F
AIR TEMP.		70 F
RELATIVE HUMIDITY		64 %
UNIT WEIGHT	C 138	145.00 pcf
BUCKET WEIGHT		8.00 lb
BUCKET + CONCRETE		44.00 lb
CONCETE WEIGHT		36.00 lb
VOLUME OF BUCKET		0.248 cf
AIR CONTENT	C231	4.30 %

MOISTURE CONTENT

	MC	AC
COARSE	0.076%	0.50%
FINE	0.074%	0.50%

MC MOISTURE CONTENT

AC ABSORPTION CONTENT

Table A.20 Hardened concrete properties of NI-0.44-5

DATE 12-Sep-03 TIME 2:00PM

MIXTURE **NI-0.44-5**

1-DAY STRENGTHS			13-Sep-03	2:00PM
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	28,550	2,272	Shear	
2	30,000	2,387	Shear	
3	27,900	2,220	Cone and Split	
AVG	28,817	2,290		

7-DAY STRENGTHS			19-Sep-03	2:00PM
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	62,947	5,009	Shear	
2	64,071	5,099	Shear	
3	63,846	5,081	Shear	
AVG	63,621	5,060		

28-DAY STRENGTHS			10-Oct-03	2:00PM
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	76,210	6,065	Shear	
2	74,861	5,957	Shear	
3	73,288	5,832	Shear	
AVG	74,786	5,950		

Table A.21 Mix design and fresh properties of NI-0.48-0

DATE	13-Aug-03	TIME	10:55 AM

MIXTURE	**NI-0.48-0**		W/C	0.59
			W/Cm	0.48
BATCH SIZE	2.30	cubic feet		

MIX PROPORTIONS						
MATERIALS	SSD AGGREGATES (PCY)	ADJUSTED FOR AGGREGATE MOISTURE (PCY)	BATCH QUANTITIES			
CEMENT	464.0	464.0	39.5	lb	17929.0	gm
FLYASH	109.0	109.0	9.3	lb	4211.8	gm
COARSE AGGREGATES	1710.0	1694.9	144.4	lb	65491.9	gm
FINE AGGREGATES	1306.0	1300.4	110.8	lb	50247.9	gm
WATER	275.0	295.7	25.2	lb	11424.4	gm
WATER ADJUSTED FOR ADMIXTURES					11412.3	gm
ADMIXTURES AE	5.2	5.2	0.4	fl oz	13.0	ml
ADMIXTURES IPNEX	0.0	0.0	0.0	fl oz	0.0	ml
ADMIXTURES $Cacl_2$	0.0	PCY	0.0	lb	0.0	gm

FRESH CONCRETE PROPERTIES

	ASTM		
SLUMP	C 143	8.00	in
CONCRETE TEMP.	C 1064	82	F
AIR TEMP.		75	F
RELATIVE HUMIDITY		68	%
UNIT WEIGHT	C 138	144	pcf
BUCKET WEIGHT		8.00	lb
BUCKET + CONCRETE		43.75	lb
CONCETE WEIGHT		35.75	lb
VOLUME OF BUCKET		0.248	cf
AIR CONTENT	C231	5.10	%

MOISTURE CONTENT

	MC	AC
COARSE	0.070%	0.96%
FINE	0.070%	0.50%

MC MOISTURE CONTENT

AC ABSORPTION CONTENT

Table A.22 Hardened concrete properties of NI-0.48-0

DATE	13-Aug-03	TIME	10:55 AM
MIXTURE	**NI-0.48-0**		

1-DAY STRENGTHS		14-Aug-2003	10:55 AM	
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	16,000	1,273	Shear	
2	16,000	1,273	Shear	
3	15,750	1,253	Cone and Split	
AVG	15,917	1,270		
7-DAY STRENGTHS		20-Aug-2003	10:55 AM	
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	48,750	3,879	Shear	
2	45,000	3,581	Shear	
3	46,500	3,700	Shear	
AVG	46,750	3,720		
28-DAY STRENGTHS		10-Sep-2003	10:55 AM	
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	63,175	5,027	Shear	
2	63,850	5,081	Shear	
3	66,550	5,296	Shear	
AVG	64,525	5,130		

Table A.23 Mix design and fresh properties of NI-0.48-5

DATE 9/12/03 TIME 3:30PM

MIXTURE **NI-0.48-5**

W/C 0.59

W/Cm 0.48

BATCH SIZE 2.25 cubic feet

MIX PROPORTIONS							
MATERIALS	SSD AGGREGATES (PCY)	ADJUSTED FOR AGGREGATE MOISTURE (PCY)	BATCH QUANTITIES				
CEMENT	464.0	464.0	38.7	lb	17539.2	gm
FLYASH	109.0	109.0	9.1	lb	4120.2	gm
COARSE AGGREGATES	1710.0	1702.8	141.9	lb	64365.3	gm
FINE AGGREGATES	1306.0	1300.5	108.4	lb	49157.5	gm
WATER	275.0	287.8	24.0	lb	10877.0	gm
WATER ADJUSTED FOR ADMIXTURES					10463.5	gm
ADMIXTURES AE	5.2	5.2	0.4	fl oz	12.7	ml
ADMIXTURES IPNEX	0.0	0.0	0.0	fl oz	0.0	ml
ADMIXTURES Cacl2	5.0	PCY	1.3	lb	590.6	gm

FRESH CONCRETE PROPERTIES

	ASTM		
SLUMP	C 143	8.50	in
CONCRETE TEMP.	C 1064	80	F
AIR TEMP.		72	F
RELATIVE HUMIDITY		64	%
UNIT WEIGHT	C 138	144.00	pcf
BUCKET WEIGHT		8.00	lb
BUCKET + CONCRETE		43.75	lb
CONCETE WEIGHT		35.75	lb
VOLUME OF BUCKET		0.2483	cf
AIR CONTENT	C231	5.30	%

MOISTURE CONTENT

	MC	AC
COARSE	0.076%	0.500%
FINE	0.074%	0.500%

MC MOISTURE CONTENT

AC ABSORPTION CONTENT

Table A.24 Hardened concrete properties of NI-0.48-5

DATE	09/12/03	TIME	3:30pm
MIXTURE	**NI-0.48-5**		

1-DAY STRENGTHS			13-Sep-2003	3:30pm
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	21,360	1,700	Shear	
2	20,460	1,628	Shear	
3	21,000	1,671	Shear	
AVG	20,940	1,670		

7-DAY STRENGTHS			19-Sep-2003	3:30pm
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	51,706	4,115	Shear	
2	49,458	3,936	Shear	
3	49,233	3,918	Shear	
AVG	50,132	3,990		

28-DAY STRENGTHS			10-Oct-2003	3:30pm
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	62,722	4,991	Shear	
2	60,923	4,848	Shear	
3	58,226	4,633	Shear	
AVG	60,624	4,820		

Table A.25 Mix design and fresh properties of I-0.40-0

DATE	3-Mar-03	TIME	2:00 PM
MIXTURE	**I-0.40-0**	W/C	0.49
		W/Cm	0.40
BATCH SIZE	1.15 cubic feet		

MIX PROPORTIONS

MATERIALS		SSD AGGREGATES (PCY)	ADJUSTED FOR AGGREGATE MOISTURE (PCY)	BATCH QUANTITIES	
CEMENT		559.0	559.0	23.8 lb	10799.9 gm
FLYASH		133.0	133.0	5.7 lb	2569.6 gm
COARSE AGGREGATES		1710.0	1703.1	72.5 lb	32904.4 gm
FINE AGGREGATES		1272.0	1267.1	54.0 lb	24479.7 gm
WATER		275.0	286.8	12.2 lb	5541.2 gm
WATER ADJUSTED FOR ADMIXTURES					5456.0 gm
ADMIXTURES	AE	6.2	6.2	0.3 fl oz	7.9 ml
	IPNEX	77.1	77.1	3.3 fl oz	97.3 ml
	Cacl2	0.0	PCY	0.0 lb	0.0 gm

FRESH CONCRETE PROPERTIES

	ASTM		
SLUMP	C 143	2.50	in
CONCRETE TEMP.	C 1064	70	F
AIR TEMP.		68	F
RELATIVE HUMIDITY		68	%
UNIT WEIGHT	C 138	146	pcf
BUCKET WEIGHT		8.00	lb
BUCKET + CONCRETE		44.25	lb
CONCETE WEIGHT		36.25	lb
VOLUME OF BUCKET		0.248	cf
AIR CONTENT	C231	leaked	%

MOISTURE CONTENT

	MC	AC
COARSE	0.096%	0.50%
FINE	0.110%	0.50%

MC MOISTURE CONTENT

AC ABSORPTION CONTENT

Table A.26 Hardened concrete properties of I-0.40-0

DATE 3-Mar-03 TIME 2:00 PM

MIXTURE **I-0.40-0**

1-DAY STRENGTHS		4-Mar-2003	2:00 PM	
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	25,628	2,039	Shear	
2	24,279	1,932	Shear	
3	26,527	2,111	Shear	
AVG	25,478	2,030		

7-DAY STRENGTHS		10-Mar-2003	2:00 PM	
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	59,124	4,705	Shear	
2	59,799	4,759	Shear	
3	58,899	4,687	Shear	
AVG	59,274	4,720		

28-DAY STRENGTHS		31-Mar-2003	2:00 PM	
	COMPRESSION			NOTES:
TEST	lb	psi	FAILURE TYPE	
1	67,892	5,403	Shear	
2	73,287	5,832	Shear	
3	64,295	5,116	Shear	
AVG	68,491	5,450		

APPENDIX B –RECORD OF ALL READINGS FOR ASTM G109

Table B.1 Record of all readings for I-0.40-2

11/4/2003						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	104.5	0	0.000	62.3	0.000
2	green	102.8	0	0.000	87.4	0.000
3	green	106.2	0	0.000	61.5	0.000
4	MMFX	106.1	0	0.000	75.6	0.000
5	MMFX	104.6	0	0.000	83.0	0.000
6	MMFX	104.7	0	0.000	88.7	0.000
12/2/2003						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	104.5	0	0.000	64.4	0.000
2	green	102.8	0	0.000	92.5	0.000
3	green	106.2	0	0.000	leaked	0.000
4	MMFX	106.1	0	0.000	77.6	0.000
5	MMFX	104.6	0	0.000	leaked	0.000
6	MMFX	104.7	0	0.000	84.6	0.000
12/30/2003						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	104.5	0	0.000	60.6	0.000
2	green	102.8	0	0.000	90.6	0.000
3	green	106.2	0	0.000	59.8	0.000
4	MMFX	106.1	0	0.000	73.6	0.000
5	MMFX	104.6	0	0.000	77.4	0.000
6	MMFX	104.7	0	0.000	77.9	0.000
1/20/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	104.5	0	0.000	49.3	0.000
2	green	102.8	0	0.000	81.2	0.000
3	green	106.2	0	0.000	48.6	0.000
4	MMFX	106.1	0	0.000	66.5	0.000
5	MMFX	104.6	0	0.000	68.2	0.000
6	MMFX	104.7	0	0.000	69.2	0.000

Table B.1 (cont.)

1/27/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	104.5	0	0.000	47.0	0.000
2	green	102.8	0	0.000	77.9	0.000
3	green	106.2	0	0.000	45.2	0.000
4	MMFX	106.1	0	0.000	60.8	0.000
5	MMFX	104.6	0	0.000	62.8	0.000
6	MMFX	104.7	0	0.000	63.3	0.000

2/3/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	104.5	0	0.000	NP	0.000
2	green	102.8	0	0.000	NP	0.000
3	green	106.2	0	0.000	NP	0.000
4	MMFX	106.1	0	0.000	NP	0.000
5	MMFX	104.6	0	0.000	NP	0.000
6	MMFX	104.7	0	0.000	NP	0.000

2/10/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	104.5	0	0.000	56.1	0.000
2	green	102.8	0	0.000	80.1	0.000
3	green	106.2	0	0.000	51.9	0.000
4	MMFX	106.1	0	0.000	72.9	0.000
5	MMFX	104.6	0	0.000	73.5	0.000
6	MMFX	104.7	0	0.000	67.4	0.000

2/17/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	104.5	0	0.000	49.5	0.000
2	green	102.8	0	0.000	80.3	0.000
3	green	106.2	0	0.000	47.1	0.000
4	MMFX	106.1	0	0.000	64.1	0.000
5	MMFX	104.6	0	0.000	65.8	0.000
6	MMFX	104.7	0	0.000	66.0	0.000

Table B.1 (cont.)

2/24/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	104.5	0	0.000	51.6	0.000
2	green	102.8	0	0.000	82.8	0.000
3	green	106.2	0	0.000	48.9	0.000
4	MMFX	106.1	0	0.000	66.5	0.000
5	MMFX	104.6	0	0.000	67.9	0.000
6	MMFX	104.7	0	0.000	68.0	0.000

3/2/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	104.5	0	0.000	NP	0.000
2	green	102.8	0	0.000	NP	0.000
3	green	106.2	0	0.000	NP	0.000
4	MMFX	106.1	0	0.000	NP	0.000
5	MMFX	104.6	0	0.000	NP	0.000
6	MMFX	104.7	0	0.000	NP	0.000

3/9/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	104.5	0	0.000	59.0	0.000
2	green	102.8	0	0.000	83.4	0.000
3	green	106.2	0	0.000	55.4	0.000
4	MMFX	106.1	0	0.000	77.7	0.000
5	MMFX	104.6	0	0.000	78.4	0.000
6	MMFX	104.7	0	0.000	70.6	0.000

3/16/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	104.5	0	0.000	52.7	0.000
2	green	102.8	0	0.000	85.2	0.000
3	green	106.2	0	0.000	49.8	0.000
4	MMFX	106.1	0	0.000	67.9	0.000
5	MMFX	104.6	0	0.000	71.2	0.000
6	MMFX	104.7	0	0.000	70.7	0.000

Table B.1 (cont.)

3/23/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	104.5	0	0.000	52.8	0.000
2	green	102.8	0	0.000	87.0	0.000
3	green	106.2	0	0.000	49.6	0.000
4	MMFX	106.1	0	0.000	68.3	0.000
5	MMFX	104.6	0	0.000	69.5	0.000
6	MMFX	104.7	0	0.000	70.8	0.000
3/30/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	104.5	0	0.000	NP	0.000
2	green	102.8	0	0.000	NP	0.000
3	green	106.2	0	0.000	NP	0.000
4	MMFX	106.1	0	0.000	NP	0.000
5	MMFX	104.6	0	0.000	NP	0.000
6	MMFX	104.7	0	0.000	NP	0.000

Table B.2 Record of all readings for I-0.40-2

10/15/2003						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	149.4	0.4	2.677	115.4	1.619
2	black	90.0	0.4	4.444	113.8	2.688
3	black	149.3	0.5	3.349	109.9	2.025
4	MMFX	91.8	0	0.000	88.8	0.000
5	MMFX	149.1	0.3	2.012	86.9	1.217
6	MMFX	121.4	0.1	0.824	88.3	0.498
11/12/2003						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	149.4	0.8	5.355	151.4	11.335
2	black	90.0	0.6	6.667	151.3	16.128
3	black	149.3	0.7	4.689	148.9	11.748
4	MMFX	91.8	0	0.000	96.1	0.000
5	MMFX	149.1	0.1	0.671	90.3	4.462
6	MMFX	121.4	0	0.000	97.2	1.495
12/10/2003						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	149.4	0.3	2.008	121.2	20.241
2	black	90.0	0.2	2.222	128.3	26.880
3	black	149.3	0.4	2.679	137.9	20.661
4	MMFX	91.8	0	0.000	77.1	0.000
5	MMFX	149.1	0	0.000	71.7	5.274
6	MMFX	121.4	0	0.000	79.3	1.495
1/7/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	149.4	0.1	0.669	98.0	22.669
2	black	90.0	0.1	1.111	105.6	29.903
3	black	149.3	0.2	1.340	114.6	24.307
4	MMFX	91.8	0	0.000	61.3	0.000
5	MMFX	149.1	0	0.000	55.3	5.274
6	MMFX	121.4	0	0.000	64.4	1.495

Table B.2 (cont.)

1/21/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	149.4	0.1	0.669	83.1	23.074
2	black	90.0	0.1	1.111	92.9	30.575
3	black	149.3	0.2	1.340	106.2	25.117
4	MMFX	91.8	0	0.000	70.5	0.000
5	MMFX	149.1	0	0.000	62.9	5.274
6	MMFX	121.4	0	0.000	72.2	1.495

1/28/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	149.4	0.1	0.669	92.3	23.479
2	black	90.0	0.1	1.111	88.4	31.247
3	black	149.3	0.1	0.670	101.9	25.725
4	MMFX	91.8	0	0.000	65.2	0.000
5	MMFX	149.1	0.1	0.671	57.7	5.477
6	MMFX	121.4	0.1	0.824	68.1	1.744

2/4/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	149.4	0.1	0.669	87.8	23.883
2	black	90.0	0.1	1.111	88.2	31.919
3	black	149.3	0.1	0.670	101.8	26.130
4	MMFX	91.8	0	0.000	63.9	0.000
5	MMFX	149.1	0	0.000	56.1	5.680
6	MMFX	121.4	0	0.000	66.5	1.993

2/11/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	149.4	0.1	0.669	NP	24.288
2	black	90.0	0	0.000	NP	32.255
3	black	149.3	0.1	0.670	NP	26.535
4	MMFX	91.8	0	0.000	NP	0.000
5	MMFX	149.1	0	0.000	NP	5.680
6	MMFX	121.4	0	0.000	NP	1.993

Table B.2 (cont.)

2/18/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	149.4	0.1	0.669	78.4	24.692
2	black	90.0	0	0.000	84.5	32.255
3	black	149.3	0.1	0.670	94.9	26.941
4	MMFX	91.8	0	0.000	71.4	0.000
5	MMFX	149.1	0	0.000	56.8	5.680
6	MMFX	121.4	0	0.000	65.1	1.993

2/25/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	149.4	0.1	0.669	85.3	25.097
2	black	90.0	0	0.000	81.8	32.255
3	black	149.3	0.1	0.670	85.9	27.346
4	MMFX	91.8	0	0.000	62.3	0.000
5	MMFX	149.1	0	0.000	53.2	5.680
6	MMFX	121.4	0	0.000	63.3	1.993

3/3/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	149.4	0.1	0.669	87.2	25.502
2	black	90.0	0.1	1.111	80.4	32.591
3	black	149.3	0.1	0.670	101.1	27.751
4	MMFX	91.8	0	0.000	63.1	0.000
5	MMFX	149.1	0	0.000	53.6	5.680
6	MMFX	121.4	0	0.000	64.0	1.993

3/10/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	149.4	0.2	1.339	NP	26.109
2	black	90.0	0.1	1.111	NP	33.263
3	black	149.3	0.2	1.340	NP	28.359
4	MMFX	91.8	0	0.000	NP	0.000
5	MMFX	149.1	0	0.000	NP	5.680
6	MMFX	121.4	0	0.000	NP	1.993

Table B.2 (cont.)

3/17/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	149.4	0.1	0.669	85.9	26.716
2	black	90.0	0	0.000	94.9	33.599
3	black	149.3	0.1	0.670	97.9	28.967
4	MMFX	91.8	0	0.000	80.9	0.000
5	MMFX	149.1	0	0.000	66.0	5.680
6	MMFX	121.4	0	0.000	78.9	1.993
3/24/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	149.4	0.1	0.669	84.3	28.335
2	black	90.0	0	0.000	79.6	35.279
3	black	149.3	0.1	0.670	90.8	31.398
4	MMFX	91.8	0	0.000	70.1	0.000
5	MMFX	149.1	0	0.000	59.9	5.680
6	MMFX	121.4	0	0.000	69.5	1.993
3/31/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	149.4	0	0.000	75.9	28.537
2	black	90.0	0	0.000	72.3	35.279
3	black	149.3	0.1	0.670	93.7	31.803
4	MMFX	91.8	0	0.000	59.8	0.000
5	MMFX	149.1	0	0.000	49.8	5.680
6	MMFX	121.4	0	0.000	58.5	1.993

Table B.3 Record of all readings for I-0.44-0

10/13/2003						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	117.5	0	0.000	N/A	0.000
2	black	118.5	0	0.000	N/A	0.000
3	black	110.8	0.1	0.903	N/A	0.546
4	MMFX	116.5	0.1	0.858	N/A	0.519
5	MMFX	117.4	0.1	0.852	N/A	0.515
6	MMFX	117.3	0.1	0.853	N/A	0.516
11/10/2003						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	117.5	0.1	0.851	79.7	1.029
2	black	118.5	0.1	0.844	85.3	1.021
3	black	110.8	0	0.000	78.6	1.638
4	MMFX	116.5	0.3	2.575	85.3	4.671
5	MMFX	117.4	0.2	1.704	94.4	3.607
6	MMFX	117.3	0.3	2.558	90.7	4.642
12/8/2003						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	117.5	0	0.000	69.1	2.059
2	black	118.5	0	0.000	77.9	2.042
3	black	110.8	0	0.000	67.7	1.638
4	MMFX	116.5	0	0.000	77.4	7.786
5	MMFX	117.4	0	0.000	95.1	5.668
6	MMFX	117.3	0	0.000	92.1	7.736
1/5/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	117.5	0	0.000	57.4	2.059
2	black	118.5	0	0.000	70.5	2.042
3	black	110.8	0	0.000	55.6	1.638
4	MMFX	116.5	0	0.000	67.4	7.786
5	MMFX	117.4	0	0.000	77.0	5.668
6	MMFX	117.3	0	0.000	79.4	7.736

Table B.3 (cont.)

1/26/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	117.5	0	0.000	57.7	2.059
2	black	118.5	0	0.000	87.0	2.042
3	black	110.8	0	0.000	54.9	1.638
4	MMFX	116.5	0	0.000	68.4	7.786
5	MMFX	117.4	0	0.000	76.6	5.668
6	MMFX	117.3	0	0.000	82.5	7.736

2/2/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	117.5	0	0.000	49.4	2.059
2	black	118.5	0	0.000	75.0	2.042
3	black	110.8	0	0.000	48.0	1.638
4	MMFX	116.5	0	0.000	60.8	7.786
5	MMFX	117.4	0	0.000	68.3	5.668
6	MMFX	117.3	0	0.000	81.2	7.736

2/9/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	117.5	0	0.000	NP	2.059
2	black	118.5	0	0.000	NP	2.042
3	black	110.8	0	0.000	NP	1.638
4	MMFX	116.5	0	0.000	NP	7.786
5	MMFX	117.4	0	0.000	NP	5.668
6	MMFX	117.3	0	0.000	NP	7.736

2/16/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	117.5	0	0.000	53.3	2.059
2	black	118.5	0	0.000	74.2	2.042
3	black	110.8	0	0.000	45.8	1.638
4	MMFX	116.5	0.1	0.858	65.4	8.046
5	MMFX	117.4	0.1	0.852	64.8	5.926
6	MMFX	117.3	0.1	0.853	81.4	7.994

Table B.3 (cont.)

2/23/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	117.5	0	0.000	65.0	2.059
2	black	118.5	0	0.000	90.8	2.042
3	black	110.8	0	0.000	82.0	1.638
4	MMFX	116.5	0	0.000	68.1	8.305
5	MMFX	117.4	0	0.000	93.7	6.183
6	MMFX	117.3	0	0.000	86.0	8.252

3/1/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	117.5	0	0.000	57.0	2.059
2	black	118.5	0	0.000	89.3	2.042
3	black	110.8	0	0.000	83.9	1.638
4	MMFX	116.5	0	0.000	63.9	8.305
5	MMFX	117.4	0	0.000	85.0	6.183
6	MMFX	117.3	0	0.000	79.4	8.252

3/8/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	117.5	0.2	1.702	NP	2.573
2	black	118.5	0.1	0.844	NP	2.297
3	black	110.8	0.2	1.805	NP	2.184
4	MMFX	116.5	0	0.000	NP	8.305
5	MMFX	117.4	0	0.000	NP	6.183
6	MMFX	117.3	0	0.000	NP	8.252

3/15/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	117.5	0	0.000	62.1	3.088
2	black	118.5	0	0.000	89.3	2.552
3	black	110.8	0	0.000	68.4	2.730
4	MMFX	116.5	0	0.000	68.3	8.305
5	MMFX	117.4	0	0.000	80.3	6.183
6	MMFX	117.3	0	0.000	82.5	8.252

Table B.3 (cont.)

3/22/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	117.5	0	0.000	61.1	3.088
2	black	118.5	0	0.000	87.7	2.552
3	black	110.8	0	0.000	66.3	2.730
4	MMFX	116.5	0	0.000	67.2	8.305
5	MMFX	117.4	0	0.000	87.3	6.183
6	MMFX	117.3	0	0.000	78.4	8.252
3/29/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	117.5	0	0.000	63.3	3.088
2	black	118.5	0	0.000	81.6	2.552
3	black	110.8	0	0.000	79.5	2.730
4	MMFX	116.5	0	0.000	64.3	8.305
5	MMFX	117.4	0	0.000	77.9	6.183
6	MMFX	117.3	0	0.000	80.3	8.252

Table B.4 Record of all readings for I-0.44-5

11/6/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	102.4	0	0.000	93.3	0.000
2	green	102.3	0	0.000	90.4	0.000
3	green	109.2	0	0.000	90.4	0.000
4	MMFX	105.1	0	0.000	99.8	0.000
5	MMFX	105.8	0	0.000	94.5	0.000
6	MMFX	105.2	0.1	0.951	109.1	0.575

12/4/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	102.4	0	0.000	92.5	0.000
2	green	102.3	0	0.000	80.4	0.000
3	green	109.2	0	0.000	leaked	0.000
4	MMFX	105.1	0	0.000	leaked	0.000
5	MMFX	105.8	0	0.000	87.2	0.000
6	MMFX	105.2	0	0.000	95.9	1.725

1/1/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	102.4	0	0.000	95.2	0.000
2	green	102.3	0	0.000	75.7	0.000
3	green	109.2	0	0.000	83.2	0.000
4	MMFX	105.1	0	0.000	105.3	0.000
5	MMFX	105.8	0	0.000	91.8	0.000
6	MMFX	105.2	0	0.000	104.0	1.725

1/22/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	102.4	0	0.000	64.5	0.000
2	green	102.3	0	0.000	60.2	0.000
3	green	109.2	0	0.000	73.1	0.000
4	MMFX	105.1	0	0.000	87.2	0.000
5	MMFX	105.8	0	0.000	77.3	0.000
6	MMFX	105.2	0	0.000	82.3	1.725

Table B.4 (cont.)

1/29/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	102.4	0	0.000	57.1	0.000
2	green	102.3	0	0.000	52.6	0.000
3	green	109.2	0	0.000	63.9	0.000
4	MMFX	105.1	0	0.000	79.9	0.000
5	MMFX	105.8	0	0.000	70.9	0.000
6	MMFX	105.2	0	0.000	75.6	1.725

2/5/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	102.4	0	0.000	NP	0.000
2	green	102.3	0	0.000	NP	0.000
3	green	109.2	0	0.000	NP	0.000
4	MMFX	105.1	0	0.000	NP	0.000
5	MMFX	105.8	0	0.000	NP	0.000
6	MMFX	105.2	0	0.000	NP	1.725

2/12/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	102.4	0	0.000	75.6	0.000
2	green	102.3	0	0.000	68.1	0.000
3	green	109.2	0	0.000	65.0	0.000
4	MMFX	105.1	0	0.000	96.1	0.000
5	MMFX	105.8	0	0.000	77.1	0.000
6	MMFX	105.2	0	0.000	93.1	1.725

2/19/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	102.4	0	0.000	63.0	0.000
2	green	102.3	0	0.000	58.6	0.000
3	green	109.2	0	0.000	70.2	0.000
4	MMFX	105.1	0	0.000	89.7	0.000
5	MMFX	105.8	0	0.000	77.5	0.000
6	MMFX	105.2	0	0.000	82.8	1.725

Table B.4 (cont.)

2/26/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	102.4	0	0.000	57.3	0.000
2	green	102.3	0	0.000	54.2	0.000
3	green	109.2	0	0.000	67.2	0.000
4	MMFX	105.1	0	0.000	81.6	0.000
5	MMFX	105.8	0	0.000	72.4	0.000
6	MMFX	105.2	0	0.000	77.3	1.725

3/4/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	102.4	0	0.000	NP	0.000
2	green	102.3	0	0.000	NP	0.000
3	green	109.2	0	0.000	NP	0.000
4	MMFX	105.1	0	0.000	NP	0.000
5	MMFX	105.8	0	0.000	NP	0.000
6	MMFX	105.2	0	0.000	NP	1.725

3/11/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	102.4	0	0.000	62.5	0.000
2	green	102.3	0	0.000	63.7	0.000
3	green	109.2	0	0.000	71.6	0.000
4	MMFX	105.1	0	0.000	87.3	0.000
5	MMFX	105.8	0	0.000	74.3	0.000
6	MMFX	105.2	0	0.000	88.8	1.725

3/18/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	102.4	0	0.000	62.4	0.000
2	green	102.3	0	0.000	59.7	0.000
3	green	109.2	0	0.000	74.1	0.000
4	MMFX	105.1	0	0.000	92.0	0.000
5	MMFX	105.8	0	0.000	76.8	0.000
6	MMFX	105.2	0	0.000	81.2	1.725

Table B.4 (cont.)

3/25/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	102.4	0	0.000	62.7	0.000
2	green	102.3	0	0.000	60.4	0.000
3	green	109.2	0	0.000	74.6	0.000
4	MMFX	105.1	0	0.000	87.5	0.000
5	MMFX	105.8	0	0.000	78.9	0.000
6	MMFX	105.2	0	0.000	83.9	1.725

4/1/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	102.4	0	0.000	NP	0.000
2	green	102.3	0	0.000	NP	0.000
3	green	109.2	0	0.000	NP	0.000
4	MMFX	105.1	0	0.000	NP	0.000
5	MMFX	105.8	0	0.000	NP	0.000
6	MMFX	105.2	0	0.000	NP	1.725

Table B.5 Record of all readings for I-0.48-0

10/28/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	108.1	0.1	0.925	88.0	0.559
2	green	106.9	0	0.000	71.6	0.000
3	green	103.8	0	0.000	73.6	0.000
4	MMFX	105.9	0	0.000	93.9	0.000
5	MMFX	105.3	0.1	0.950	102.8	0.575
6	MMFX	104.4	0	0.000	94.4	0.000

11/25/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	108.1	0	0.000	96.3	1.678
2	green	106.9	0	0.000	79.7	0.000
3	green	103.8	0	0.000	73.2	0.000
4	MMFX	105.9	0	0.000	91.0	0.000
5	MMFX	105.3	0.1	0.950	93.3	2.873
6	MMFX	104.4	0	0.000	N/A	0.000

12/23/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	108.1	0	0.000	89.9	1.678
2	green	106.9	0	0.000	78.9	0.000
3	green	103.8	0	0.000	69.9	0.000
4	MMFX	105.9	0	0.000	85.1	0.000
5	MMFX	105.3	0	0.000	89.6	4.022
6	MMFX	104.4	0	0.000	86.2	0.000

1/20/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	108.1	0	0.000	N/A	1.678
2	green	106.9	0	0.000	N/A	0.000
3	green	103.8	0	0.000	N/A	0.000
4	MMFX	105.9	0	0.000	N/A	0.000
5	MMFX	105.3	0	0.000	N/A	4.022
6	MMFX	104.4	0	0.000	N/A	0.000

Table B.5 (cont.)

1/27/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	108.1	0	0.000	NP	1.678
2	green	106.9	0	0.000	NP	0.000
3	green	103.8	0	0.000	NP	0.000
4	MMFX	105.9	0	0.000	NP	0.000
5	MMFX	105.3	0	0.000	NP	4.022
6	MMFX	104.4	0	0.000	NP	0.000

2/3/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	108.1	0	0.000	75.8	1.678
2	green	106.9	0	0.000	70.8	0.000
3	green	103.8	0	0.000	56.0	0.000
4	MMFX	105.9	0	0.000	76.6	0.000
5	MMFX	105.3	0	0.000	81.0	4.022
6	MMFX	104.4	0	0.000	70.3	0.000

2/10/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	108.1	0	0.000	79.7	1.678
2	green	106.9	0	0.000	67.3	0.000
3	green	103.8	0	0.000	60.2	0.000
4	MMFX	105.9	0	0.000	71.1	0.000
5	MMFX	105.3	0	0.000	75.1	4.022
6	MMFX	104.4	0	0.000	67.0	0.000

2/17/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	108.1	0	0.000	78.7	1.678
2	green	106.9	0	0.000	66.4	0.000
3	green	103.8	0	0.000	250.5	0.000
4	MMFX	105.9	0	0.000	73.1	0.000
5	MMFX	105.3	0	0.000	74.6	4.022
6	MMFX	104.4	0	0.000	72.3	0.000

Table B.5 (cont.)

2/24/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	108.1	0	0.000	NP	1.678
2	green	106.9	0	0.000	NP	0.000
3	green	103.8	0	0.000	NP	0.000
4	MMFX	105.9	0	0.000	NP	0.000
5	MMFX	105.3	0	0.000	NP	4.022
6	MMFX	104.4	0	0.000	NP	0.000

3/2/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	108.1	0	0.000	79.9	1.678
2	green	106.9	0	0.000	76.4	0.000
3	green	103.8	0	0.000	224.1	0.000
4	MMFX	105.9	0	0.000	86.9	0.000
5	MMFX	105.3	0	0.000	88.8	4.022
6	MMFX	104.4	0	0.000	74.2	0.000

3/9/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	108.1	0	0.000	83.1	1.678
2	green	106.9	0	0.000	69.7	0.000
3	green	103.8	0	0.000	238.3	0.000
4	MMFX	105.9	0	0.000	74.6	0.000
5	MMFX	105.3	0	0.000	80.6	4.022
6	MMFX	104.4	0	0.000	71.5	0.000

3/16/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	108.1	0	0.000	84.0	1.678
2	green	106.9	0	0.000	69.5	0.000
3	green	103.8	0	0.000	207	0.000
4	MMFX	105.9	0	0.000	76.3	0.000
5	MMFX	105.3	0	0.000	82.5	4.022
6	MMFX	104.4	0	0.000	73.3	0.000

Table B.5 (cont.)

3/23/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	108.1	0	0.000	NP	1.678
2	green	106.9	0	0.000	NP	0.000
3	green	103.8	0	0.000	NP	0.000
4	MMFX	105.9	0	0.000	NP	0.000
5	MMFX	105.3	0	0.000	NP	4.022
6	MMFX	104.4	0	0.000	NP	0.000
3/30/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	108.1	0	0.000	69.4	1.678
2	green	106.9	0	0.000	68.3	0.000
3	green	103.8	0	0.000	159.5	0.000
4	MMFX	105.9	0	0.000	75.4	0.000
5	MMFX	105.3	0	0.000	85.0	4.022
6	MMFX	104.4	0	0.000	62.5	0.000

Table B.6 Record of all readings for I-0.48-2

10/14/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	89.7	0.2	2.230	N/A	1.349
2	black	82.0	0.1	1.220	N/A	0.738
3	black	82.3	0	0.000	N/A	0.000
4	MMFX	91.7	0.1	1.091	N/A	0.660
5	MMFX	90.0	0.1	1.111	N/A	0.672
6	MMFX	81.7	0	0.000	N/A	0.000

11/11/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	89.7	4	44.593	276.1	57.986
2	black	82.0	0.2	2.439	111.8	5.164
3	black	82.3	2.5	30.377	261.4	36.744
4	MMFX	91.7	0	0.000	101.3	1.980
5	MMFX	90.0	0.5	5.556	105.8	8.736
6	MMFX	81.7	0	0.000	102.5	0.000

12/9/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	89.7	3.4	37.904	275.7	157.774
2	black	82.0	0.2	2.439	121.6	11.064
3	black	82.3	1.9	23.086	253.8	101.413
4	MMFX	91.7	0	0.000	90.1	1.980
5	MMFX	90.0	0	0.000	89.9	15.457
6	MMFX	81.7	0	0.000	89.8	0.000

1/6/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	89.7	0.3	3.344	leaked	195.194
2	black	82.0	0.1	1.220	113.1	14.384
3	black	82.3	1	12.151	232.6	133.380
4	MMFX	91.7	0	0.000	74.8	1.980
5	MMFX	90.0	0	0.000	73.9	15.457
6	MMFX	81.7	0	0.000	77.0	0.000

Table B.6 (cont.)

1/20/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	89.7	0.2	2.230	114.5	196.880
2	black	82.0	0.1	1.220	89.8	15.122
3	black	82.3	0.1	1.215	134.6	137.422
4	MMFX	91.7	0	0.000	79.2	1.980
5	MMFX	90.0	0	0.000	77.2	15.457
6	MMFX	81.7	0	0.000	77.4	0.000

1/27/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	89.7	1.2	13.378	257	201.600
2	black	82.0	0.1	1.220	91.3	15.859
3	black	82.3	0.8	9.721	225.1	140.729
4	MMFX	91.7	0	0.000	74.2	1.980
5	MMFX	90.0	0	0.000	68.7	15.457
6	MMFX	81.7	0	0.000	70.1	0.000

2/3/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	89.7	0.9	10.033	263.1	208.679
2	black	82.0	0	0.000	94.8	16.228
3	black	82.3	1.6	19.441	240.3	149.547
4	MMFX	91.7	0	0.000	71.6	1.980
5	MMFX	90.0.	0	0.000	67.6	15.457
6	MMFX	81.7	0	0.000	68.8	0.000

2/10/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	89.7	0.6	6.689	NP	213.736
2	black	82.0	0.1	1.220	NP	16.597
3	black	82.3	0.4	4.860	NP	156.896
4	MMFX	91.7	0	0.000	NP	1.980
5	MMFX	90.0	0	0.000	NP	15.457
6	MMFX	81.7	0	0.000	NP	0.000

Table B.6 (cont.)

2/17/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	89.7	0.4	4.459	193.2	217.107
2	black	82.0	0	0.000	80.1	16.966
3	black	82.3	0.3	3.645	171.8	159.468
4	MMFX	91.7	0	0.000	70.7	1.980
5	MMFX	90.0	0	0.000	61.4	15.457
6	MMFX	81.7	0	0.000	82.1	0.000

2/24/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	89.7	1.4	15.608	249.6	223.175
2	black	82.0	0.1	1.220	89.7	17.335
3	black	82.3	1	12.151	229.7	164.245
4	MMFX	91.7	0	0.000	83.7	1.980
5	MMFX	90.0	0	0.000	72.7	15.457
6	MMFX	81.7	0	0.000	72.5	0.000

3/2/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	89.7	1.2	13.378	240.6	231.941
2	black	82.0	0	0.000	97.8	17.704
3	black	82.3	1	12.151	233.9	171.594
4	MMFX	91.7	0	0.000	91.0	1.980
5	MMFX	90.0	0.1	1.111	73.3	15.793
6	MMFX	81.7	0	0.000	72.0	0.000

3/9/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	89.7	0.7	7.804	NP	238.346
2	black	82.0	0.1	1.220	NP	18.073
3	black	82.3	0.6	7.290	NP	177.473
4	MMFX	91.7	0	0.000	NP	1.980
5	MMFX	90.0	0	0.000	NP	16.129
6	MMFX	81.7	0	0.000	NP	0.000

Table B.6 (cont.)

3/16/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	89.7	0.3	3.344	170.8	241.717
2	black	82.0	0	0.000	89.7	18.442
3	black	82.3	0.2	2.430	144.1	180.412
4	MMFX	91.7	0	0.000	90.3	1.980
5	MMFX	90.0	0	0.000	72.2	16.129
6	MMFX	81.7	0	0.000	89.9	0.000

3/23/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	89.7	0.7	7.804	203.6	259.248
2	black	82.0	0	0.000	86.0	20.286
3	black	82.3	0.2	2.430	157.8	196.579
4	MMFX	91.7	0	0.000	92.3	1.980
5	MMFX	90.0	0	0.000	76.6	16.129
6	MMFX	81.7	0	0.000	75.4	0.000

3/30/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	89.7	0.8	8.919	215.5	264.305
2	black	82.0	0	0.000	93.6	20.286
3	black	82.3	0.1	1.215	134.6	197.681
4	MMFX	91.7	0	0.000	89.9	1.980
5	MMFX	90.0	0	0.000	75.8	16.129
6	MMFX	81.7	0	0.000	71.0	0.000

Table B.7 Record of all readings for NI-0.40-0

10/30/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.4	0	0.000	80.5	0.000
2	black	104.2	0	0.000	80.3	0.000
3	black	104.2	0	0.000	79.2	0.000
4	green	106.3	0	0.000	78.2	0.000
5	green	107.6	0	0.000	71.1	0.000
6	green	105.2	0	0.000	98.9	0.000

11/27/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.4	0	0.000	77.3	0.000
2	black	104.2	0	0.000	100.0	0.000
3	black	104.2	0	0.000	79.2	0.000
4	green	106.3	0	0.000	78.1	0.000
5	green	107.6	0	0.000	92.0	0.000
6	green	105.2	0	0.000	106.3	0.000

12/25/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.4	0	0.000	75.9	0.000
2	black	104.2	0	0.000	95.9	0.000
3	black	104.2	0	0.000	78.1	0.000
4	green	106.3	0	0.000	75.4	0.000
5	green	107.6	0	0.000	87.3	0.000
6	green	105.2	0	0.000	102.6	0.000

1/22/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.4	0	0.000	73.8	0.000
2	black	104.2	0	0.000	88.6	0.000
3	black	104.2	0	0.000	75.7	0.000
4	green	106.3	0	0.000	71.3	0.000
5	green	107.6	0	0.000	83.6	0.000
6	green	105.2	0	0.000	97.4	0.000

Table B.7 (cont.)

1/29/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.4	0	0.000	NP	0.000
2	black	104.2	0	0.000	NP	0.000
3	black	104.2	0	0.000	NP	0.000
4	green	106.3	0	0.000	NP	0.000
5	green	107.6	0	0.000	NP	0.000
6	green	105.2	0	0.000	NP	0.000

2/5/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.4	0	0.000	83.0	0.000
2	black	104.2	0	0.000	100.1	0.000
3	black	104.2	0	0.000	85.1	0.000
4	green	106.3	0	0.000	84.0	0.000
5	green	107.6	0	0.000	90.6	0.000
6	green	105.2	0	0.000	107.3	0.000

2/12/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.4	0	0.000	66.5	0.000
2	black	104.2	0	0.000	85.4	0.000
3	black	104.2	0	0.000	73.9	0.000
4	green	106.3	0	0.000	79.6	0.000
5	green	107.6	0	0.000	80.7	0.000
6	green	105.2	0	0.000	96.3	0.000

2/19/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.4	0	0.000	70.4	0.000
2	black	104.2	0	0.000	88.7	0.000
3	black	104.2	0	0.000	76.4	0.000
4	green	106.3	0	0.000	79.8	0.000
5	green	107.6	0	0.000	88.1	0.000
6	green	105.2	0	0.000	100.6	0.000

Table B.7 (cont.)

2/26/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.4	0	0.000	NP	0.000
2	black	104.2	0	0.000	NP	0.000
3	black	104.2	0	0.000	NP	0.000
4	green	106.3	0	0.000	NP	0.000
5	green	107.6	0	0.000	NP	0.000
6	green	105.2	0	0.000	NP	0.000

3/4/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.4	0	0.000	83.2	0.000
2	black	104.2	0	0.000	104.2	0.000
3	black	104.2	0	0.000	91.7	0.000
4	green	106.3	0	0.000	88.4	0.000
5	green	107.6	0	0.000	94.3	0.000
6	green	105.2	0	0.000	115.8	0.000

3/11/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.4	0	0.000	70.7	0.000
2	black	104.2	0	0.000	90.1	0.000
3	black	104.2	0	0.000	69.2	0.000
4	green	106.3	0	0.000	75.9	0.000
5	green	107.6	0	0.000	85.3	0.000
6	green	105.2	0	0.000	104.1	0.000

3/18/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.4	0	0.000	70.1	0.000
2	black	104.2	0	0.000	89.1	0.000
3	black	104.2	0	0.000	73.4	0.000
4	green	106.3	0	0.000	74.5	0.000
5	green	107.6	0	0.000	84.9	0.000
6	green	105.2	0	0.000	102.9	0.000

Table B.7 (cont.)

3/25/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.4	0	0.000	NP	0.000
2	black	104.2	0	0.000	NP	0.000
3	black	104.2	0	0.000	NP	0.000
4	green	106.3	0	0.000	NP	0.000
5	green	107.6	0	0.000	NP	0.000
6	green	105.2	0	0.000	NP	0.000

4/1/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.4	0	0.000	89.3	0.000
2	black	104.2	0	0.000	108.0	0.000
3	black	104.2	0	0.000	93.4	0.000
4	green	106.3	0	0.000	94.4	0.000
5	green	107.6	0	0.000	101.4	0.000
6	green	105.2	0	0.000	118.3	0.000

Table B.8 Record of all readings for NI-0.40-2

11/18/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	105.2	0	0.000	59.1	0.000
2	green	104.0	0	0.000	86.9	0.000
3	green	104.8	0	0.000	93.6	0.000
4	MMFX	105.1	0	0.000	78.8	0.000
5	MMFX	106.3	0.1	0.941	80.5	0.569
6	MMFX	104.3	0.1	0.959	82.0	0.580

12/16/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	105.2	0	0.000	43.7	0.000
2	green	104.0	0	0.000	72.3	0.000
3	green	104.8	0	0.000	79.7	0.000
4	MMFX	105.1	0	0.000	58.5	0.000
5	MMFX	106.3	0	0.000	63.9	1.707
6	MMFX	104.3	0	0.000	60.7	1.740

1/13/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	105.2	0	0.000	38.3	0.000
2	green	104.0	0	0.000	67.6	0.000
3	green	104.8	0	0.000	77.1	0.000
4	MMFX	105.1	0	0.000	56.3	0.000
5	MMFX	106.3	0.1	0.941	60.3	2.846
6	MMFX	104.3	0	0.000	54.0	1.740

1/20/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	105.2	0	0.000	NP	0.000
2	green	104.0	0	0.000	NP	0.000
3	green	104.8	0	0.000	NP	0.000
4	MMFX	105.1	0	0.000	NP	0.000
5	MMFX	106.3	0	0.000	NP	3.699
6	MMFX	104.3	0	0.000	NP	1.740

Table B.8 (cont.)

2/3/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	105.2	0	0.000	22.9	0.000
2	green	104.0	0	0.000	51.7	0.000
3	green	104.8	0	0.000	61.6	0.000
4	MMFX	105.1	0	0.000	42.8	0.000
5	MMFX	106.3	0	0.000	41.1	3.699
6	MMFX	104.3	0	0.000	39.9	1.740
2/10/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	105.2	0	0.000	24.4	0.000
2	green	104.0	0	0.000	54.1	0.000
3	green	104.8	0	0.000	64.9	0.000
4	MMFX	105.1	0	0.000	45.2	0.000
5	MMFX	106.3	0	0.000	45.1	3.699
6	MMFX	104.3	0	0.000	44.4	8.998
2/17/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	105.2	0	0.000	NP	0.000
2	green	104.0	0	0.000	NP	0.000
3	green	104.8	0	0.000	NP	0.000
4	MMFX	105.1	0	0.000	NP	0.000
5	MMFX	106.3	0	0.000	NP	3.699
6	MMFX	104.3	0	0.000	NP	16.255
2/24/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	105.2	0	0.000	39.0	0.000
2	green	104.0	0	0.000	76.7	0.000
3	green	104.8	0	0.000	93.4	0.000
4	MMFX	105.1	0	0.000	57.7	0.000
5	MMFX	106.3	0	0.000	76.1	3.699
6	MMFX	104.3	0	0.000	59.9	16.255

Table B.8 (cont.)

3/2/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	105.2	0	0.000	21.2	0.000
2	green	104.0	0	0.000	46.0	0.000
3	green	104.8	0	0.000	56.0	0.000
4	MMFX	105.1	0	0.000	32.8	0.000
5	MMFX	106.3	0	0.000	33.1	3.699
6	MMFX	104.3	0	0.000	30.9	16.255

3/9/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	105.2	0	0.000	23.9	0.000
2	green	104.0	0	0.000	47.3	0.000
3	green	104.8	0	0.000	56.4	0.000
4	MMFX	105.1	0	0.000	36.3	0.000
5	MMFX	106.3	0	0.000	30.5	3.699
6	MMFX	104.3	0	0.000	26.5	16.255

3/16/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	105.2	0	0.000	NP	0.000
2	green	104.0	0	0.000	NP	0.000
3	green	104.8	0	0.000	NP	0.000
4	MMFX	105.1	0	0.000	NP	0.000
5	MMFX	106.3	0	0.000	NP	3.699
6	MMFX	104.3	0	0.000	NP	16.255

3/23/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	105.2	0	0.000	35.1	0.000
2	green	104.0	0	0.000	60.3	0.000
3	green	104.8	0	0.000	67.4	0.000
4	MMFX	105.1	0	0.000	32.3	0.000
5	MMFX	106.3	0	0.000	38.1	3.130
6	MMFX	104.3	0	0.000	22.9	16.255

Table B.8 (cont.)

3/30/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	105.2	0	0.000	22.9	0.000
2	green	104.0	0	0.000	51.1	0.000
3	green	104.8	0	0.000	60.1	0.000
4	MMFX	105.1	0	0.000	41.0	0.000
5	MMFX	106.3	0	0.000	40.7	3.130
6	MMFX	104.3	0	0.000	39.8	16.255

Table B.9 Record of all readings for NI-0.44-2

11/14/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.2	0.1	0.951	86.2	0.575
2	black	104.3	0.2	1.918	126.5	1.160
3	black	105.5	0.1	0.948	97.6	0.573
4	green	105.5	0	0.000	58.6	0.000
5	green	105.7	0	0.000	41.8	0.000
6	green	103.6	0	0.000	76.3	0.000

12/12/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.2	0	0.000	78.9	1.725
2	black	104.3	0.1	0.959	122.0	4.640
3	black	105.5	0.1	0.948	96.0	2.867
4	green	105.5	0	0.000	44.7	0.000
5	green	105.7	0	0.000	25.2	0.000
6	green	103.6	0	0.000	55.8	0.000

1/9/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.2	0	0.000	73.2	1.725
2	black	104.3	0.1	0.959	108.6	6.960
3	black	105.5	0.1	0.948	84.8	5.160
4	green	105.5	0	0.000	37.2	0.000
5	green	105.7	0	0.000	14.0	0.000
6	green	103.6	0	0.000	46.5	0.000

1/23/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.2	0	0.000	68.4	1.725
2	black	104.3	0.1	0.959	108.6	8.700
3	black	105.5	0.1	0.948	83.1	6.880
4	green	105.5	0	0.000	55.6	0.000
5	green	105.7	0	0.000	33.9	0.000
6	green	103.6	0	0.000	62.2	0.000

Table B.9 (cont.)

1/30/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.2	0	0.000	54.1	1.725
2	black	104.3	0.1	0.959	82.7	9.280
3	black	105.5	0	0.000	68.2	7.167
4	green	105.5	0	0.000	25.5	0.000
5	green	105.7	0	0.000	5.8	0.000
6	green	103.6	0	0.000	34.1	0.000

2/6/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.2	0	0.000	54.8	1.725
2	black	104.3	0	0.000	89.1	9.570
3	black	105.5	0	0.000	75.4	7.167
4	green	105.5	0	0.000	26.5	0.000
5	green	105.7	0	0.000	6.7	0.000
6	green	103.6	0	0.000	35.7	0.000

2/13/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.2	0	0.000	NP	1.725
2	black	104.3	0	0.000	NP	9.570
3	black	105.5	0	0.000	NP	7.167
4	green	105.5	0	0.000	NP	0.000
5	green	105.7	0	0.000	NP	0.000
6	green	103.6	0	0.000	NP	0.000

2/20/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.2	0	0.000	64.6	1.725
2	black	104.3	0	0.000	95.9	9.570
3	black	105.5	0	0.000	79.5	7.167
4	green	105.5	0	0.000	47.0	0.000
5	green	105.7	0	0.000	27.5	0.000
6	green	103.6	0	0.000	56.8	0.000

Table B.9 (cont.)

2/27/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.2	0	0.000	48.7	1.725
2	black	104.3	0	0.000	77.4	9.570
3	black	105.5	0	0.000	68.4	7.167
4	green	105.5	0	0.000	27.0	0.000
5	green	105.7	0	0.000	9.9	0.000
6	green	103.6	0	0.000	39.0	0.000
3/5/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.2	0	0.000	51.9	1.725
2	black	104.3	0	0.000	85.8	9.570
3	black	105.5	0	0.000	75.7	7.167
4	green	105.5	0	0.000	28.0	0.000
5	green	105.7	0	0.000	11.3	0.000
6	green	103.6	0	0.000	40.4	0.000
3/12/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.2	0	0.000	NP	1.725
2	black	104.3	0	0.000	NP	9.570
3	black	105.5	0	0.000	NP	7.167
4	green	105.5	0	0.000	NP	0.000
5	green	105.7	0	0.000	NP	0.000
6	green	103.6	0	0.000	NP	0.000
3/19/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.2	0	0.000	52.1	1.725
2	black	104.3	0	0.000	90.1	9.570
3	black	105.5	0	0.000	72.6	7.167
4	green	105.5	0	0.000	45.6	0.000
5	green	105.7	0	0.000	28.6	0.000
6	green	103.6	0	0.000	56.4	0.000

Table B.9 (cont.)

3/26/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.2	0	0.000	46.9	1.725
2	black	104.3	0	0.000	74.3	8.990
3	black	105.5	0	0.000	74.0	6.594
4	green	105.5	0	0.000	27.0	0.000
5	green	105.7	0	0.000	11.5	0.000
6	green	103.6	0	0.000	40.2	0.000

4/2/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.2	0	0.000	39.2	1.725
2	black	104.3	0	0.000	76.1	8.990
3	black	105.5	0	0.000	73.0	6.594
4	green	105.5	0	0.000	22.8	0.000
5	green	105.7	0	0.000	5.8	0.000
6	green	103.6	0	0.000	34.1	0.000

Table B.10 Record of all readings for NI-0.44-5

11/21/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	99.7	0	0.000	74.3	0.000
2	green	105.2	0	0.000	102.5	0.000
3	green	105.0	0	0.000	94.8	0.000
4	MMFX	105.8	0	0.000	120.2	0.000
5	MMFX	105.7	0.1	0.946	98.9	0.572
6	MMFX	103.3	0.1	0.968	115.9	0.585

12/19/2003

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	99.7	0	0.000	58.1	0.000
2	green	105.2	0	0.000	74.5	0.000
3	green	105.0	0	0.000	75.2	0.000
4	MMFX	105.8	0	0.000	94.0	0.000
5	MMFX	105.7	0	0.000	84.6	1.716
6	MMFX	103.3	0	0.000	99.9	1.756

1/16/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	99.7	0	0.000	53.3	0.000
2	green	105.2	0	0.000	66.3	0.000
3	green	105.0	0	0.000	71.6	0.000
4	MMFX	105.8	0	0.000	89.8	0.000
5	MMFX	105.7	0	0.000	72.9	1.716
6	MMFX	103.3	0	0.000	86.8	1.756

1/23/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	99.7	0	0.000	NP	0.000
2	green	105.2	0	0.000	NP	0.000
3	green	105.0	0	0.000	NP	0.000
4	MMFX	105.8	0	0.000	NP	0.000
5	MMFX	105.7	0	0.000	NP	1.716
6	MMFX	103.3	0	0.000	NP	1.756

Table B.10 (cont.)

1/30/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	99.7	0	0.000	66.8	0.000
2	green	105.2	0	0.000	62.5	0.000
3	green	105.0	0	0.000	77.1	0.000
4	MMFX	105.8	0	0.000	89.5	0.000
5	MMFX	105.7	0	0.000	82.1	1.716
6	MMFX	103.3	0	0.000	84.7	1.756

2/6/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	99.7	0	0.000	42.8	0.000
2	green	105.2	0	0.000	47.1	0.000
3	green	105.0	0	0.000	59.9	0.000
4	MMFX	105.8	0	0.000	76.1	0.000
5	MMFX	105.7	0	0.000	60.7	1.716
6	MMFX	103.3	0	0.000	75.7	1.756

2/13/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	99.7	0	0.000	39.2	0.000
2	green	105.2	0	0.000	43.3	0.000
3	green	105.0	0	0.000	55.2	0.000
4	MMFX	105.8	0	0.000	71.9	0.000
5	MMFX	105.7	0	0.000	56.9	1.716
6	MMFX	103.3	0	0.000	71.8	1.756

2/20/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	99.7	0	0.000	NP	0.000
2	green	105.2	0	0.000	NP	0.000
3	green	105.0	0	0.000	NP	0.000
4	MMFX	105.8	0	0.000	NP	0.000
5	MMFX	105.7	0	0.000	NP	1.716
6	MMFX	103.3	0	0.000	NP	1.756

Table B.10 (cont.)

2/27/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	99.7	0	0.000	65.2	0.000
2	green	105.2	0	0.000	60.6	0.000
3	green	105.0	0	0.000	75.3	0.000
4	MMFX	105.8	0	0.000	92.8	0.000
5	MMFX	105.7	0	0.000	81.6	1.716
6	MMFX	103.3	0	0.000	88.8	1.756

3/5/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	99.7	0	0.000	46.4	0.000
2	green	105.2	0	0.000	55.2	0.000
3	green	105.0	0	0.000	68.1	0.000
4	MMFX	105.8	0	0.000	78.6	0.000
5	MMFX	105.7	0	0.000	61.3	1.716
6	MMFX	103.3	0	0.000	78.3	1.756

3/12/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	99.7	0	0.000	42.7	0.000
2	green	105.2	0	0.000	55.0	0.000
3	green	105.0	0	0.000	63.9	0.000
4	MMFX	105.8	1.6	15.123	211.8	4.573
5	MMFX	105.7	0	0.000	62.8	1.716
6	MMFX	103.3	0	0.000	79.5	1.756

3/19/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	99.7	0	0.000	NP	0.000
2	green	105.2	0	0.000	NP	0.000
3	green	105.0	0	0.000	NP	0.000
4	MMFX	105.8	1.3	12.287	NP	12.862
5	MMFX	105.7	0	0.000	NP	1.716
6	MMFX	103.3	0	0.000	NP	1.756

Table B.10 (cont.)

3/26/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	99.7	0	0.000	60.8	0.000
2	green	105.2	0	0.000	66.4	0.000
3	green	105.0	0	0.000	87.1	0.000
4	MMFX	105.8	1.0	9.452	204.8	19.436
5	MMFX	105.7	0	0.000	79.3	1.716
6	MMFX	103.3	0	0.000	88.3	1.756
4/2/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	99.7	0	0.000	42.5	0.000
2	green	105.2	0	0.000	48.4	0.000
3	green	105.0	0	0.000	62.1	0.000
4	MMFX	105.8	1.4	13.233	222.6	26.296
5	MMFX	105.7	0	0.000	57.7	1.716
6	MMFX	103.3	0	0.000	76.6	1.756

Table B.11 Record of all readings for NI-0.48-0

10/22/2003						
Specimen Num.	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	103.8	0	0.000	96.6	0.000
2	green	105.8	0	0.000	86.0	0.000
3	green	105.0	0	0.000	88.8	0.000
4	MMFX	102.0	0.1	0.980	121.6	0.593
5	MMFX	105.8	0.1	0.945	110.4	0.572
6	MMFX	106.3	0.1	0.941	122.9	0.569
11/19/2003						
Specimen Num.	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coul.)
1	green	103.8	0	0.000	103.2	0.000
2	green	105.8	0	0.000	84.2	0.000
3	green	105.0	0	0.000	89.7	0.000
4	MMFX	102.0	0	0.000	113.0	1.778
5	MMFX	105.8	0	0.000	100.4	1.715
6	MMFX	106.3	0	0.000	117.1	1.707
12/17/2003						
Specimen Num.	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coul.)
1	green	103.8	0	0.000	96.7	0.000
2	green	105.8	0	0.000	85.8	0.000
3	green	105.0	0	0.000	78.8	0.000
4	MMFX	102.0	0	0.000	107.3	1.778
5	MMFX	105.8	0	0.000	91.7	1.715
6	MMFX	106.3	0	0.000	107.4	1.707
1/14/2004						
Specimen Num.	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coul.)
1	green	103.8	0	0.000	90.0	0.000
2	green	105.8	0	0.000	81.1	0.000
3	green	105.0	0	0.000	76.8	0.000
4	MMFX	102.0	0	0.000	97.1	1.778
5	MMFX	105.8	0	0.000	85.9	1.715
6	MMFX	106.3	0	0.000	97.4	1.707

Table B.11 (cont.)

1/21/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coul.)
1	green	103.8	0	0.000	NP	0.000
2	green	105.8	0	0.000	NP	0.000
3	green	105.0	0	0.000	NP	0.000
4	MMFX	102.0	0	0.000	NP	1.778
5	MMFX	105.8	0	0.000	NP	1.715
6	MMFX	106.3	0	0.000	NP	1.707

1/28/2004

Specimen Num.	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coul.)
1	green	103.8	0	0.000	77.6	0.000
2	green	105.8	0	0.000	76.4	0.000
3	green	105.0	0	0.000	78.3	0.000
4	MMFX	102.0	0	0.000	100.3	1.778
5	MMFX	105.8	0	0.000	81.9	1.715
6	MMFX	106.3	0	0.000	92.1	1.707

2/4/2004

Specimen Num.	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coul.)
1	green	103.8	0	0.000	82.2	0.000
2	green	105.8	0	0.000	72.0	0.000
3	green	105.0	0	0.000	72.3	0.000
4	MMFX	102.0	0	0.000	93.5	1.778
5	MMFX	105.8	0	0.000	79.4	1.715
6	MMFX	106.3	0	0.000	91.1	1.707

2/11/2004

Specimen Num.	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coul.)
1	green	103.8	0	0.000	83.1	0.000
2	green	105.8	0	0.000	73.7	0.000
3	green	105.0	0	0.000	74.2	0.000
4	MMFX	102.0	0	0.000	95.2	1.778
5	MMFX	105.8	0	0.000	80.3	1.715
6	MMFX	106.3	0	0.000	87.6	1.707

Table B.11 (cont.)

2/18/2004

Specimen Num.	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	103.8	0	0.000	NP	0.000
2	green	105.8	0	0.000	NP	0.000
3	green	105.0	0	0.000	NP	0.000
4	MMFX	102.0	0	0.000	NP	1.778
5	MMFX	105.8	0	0.000	NP	1.715
6	MMFX	106.3	0	0.000	NP	1.707

2/25/2004

Specimen Num.	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	103.8	0	0.000	81.6	0.000
2	green	105.8	0	0.000	77.0	0.000
3	green	105.0	0	0.000	83.6	0.000
4	MMFX	102.0	0	0.000	101.5	1.778
5	MMFX	105.8	0	0.000	81.5	1.715
6	MMFX	106.3	0	0.000	93.0	1.707

3/3/2004

Specimen Num.	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	103.8	0	0.000	85.1	0.000
2	green	105.8	0	0.000	84.3	0.000
3	green	105.0	0	0.000	78.3	0.000
4	MMFX	102.0	0	0.000	98.9	1.778
5	MMFX	105.8	0	0.000	78.7	1.715
6	MMFX	106.3	0	0.000	97.7	1.707

3/10/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	103.8	0	0.000	86.6	0.000
2	green	105.8	0	0.000	78.9	0.000
3	green	105.0	0	0.000	82.9	0.000
4	MMFX	102.0	0	0.000	97.3	1.778
5	MMFX	105.8	0	0.000	79.7	1.715
6	MMFX	106.3	0	0.000	96.5	1.707

Table B.11 (cont.)

3/17/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	103.8	0	0.000	NP	0.000
2	green	105.8	0	0.000	NP	0.000
3	green	105.0	0	0.000	NP	0.000
4	MMFX	102.0	0	0.000	NP	1.778
5	MMFX	105.8	0	0.000	NP	1.715
6	MMFX	106.3	0	0.000	NP	1.707

3/24/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	103.8	0	0.000	86.5	0.000
2	green	105.8	0	0.000	79.1	0.000
3	green	105.0	0	0.000	87.2	0.000
4	MMFX	102.0	0	0.000	104.8	1.778
5	MMFX	105.8	0	0.000	87.7	1.715
6	MMFX	106.3	0	0.000	99.9	1.707

3/31/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	green	103.8	0	0.000	85.5	0.000
2	green	105.8	0	0.000	76.5	0.000
3	green	105.0	0	0.000	79.4	0.000
4	MMFX	102.0	0	0.000	93.7	1.778
5	MMFX	105.8	0	0.000	84	1.715
6	MMFX	106.3	0	0.000	94.4	1.707

Table B.12 Record of all readings for NI-0.48-5

11/21/2003						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.3	2.1	19.943	179.2	12.062
2	black	104.4	0.3	2.874	125.8	1.738
3	black	103.9	1.9	18.287	190.0	11.060
4	green	104.6	0	0.000	95.0	0.000
5	green	104.5	0.9	8.612	158.4	5.209
6	green	104.3	0	0.000	70.8	0.000
12/19/2003						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.3	N/A	N/A	126.5	N/A
2	black	104.4	N/A	N/A	125.1	N/A
3	black	103.9	N/A	N/A	161.7	N/A
4	green	104.6	N/A	N/A	81.5	N/A
5	green	104.5	N/A	N/A	86.4	N/A
6	green	104.3	N/A	N/A	54.7	N/A
1/16/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.3	0.3	2.849	117.1	67.200
2	black	104.4	0.3	2.874	123.8	15.644
3	black	103.9	1.1	10.587	178.2	80.912
4	green	104.6	0	0.000	65.6	0.000
5	green	104.5	0	0.000	80.3	26.043
6	green	104.3	0	0.000	51.2	0.000
1/23/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.3	0.1	0.950	NP	70.646
2	black	104.4	0.1	0.958	NP	19.120
3	black	103.9	0.4	3.850	NP	94.009
4	green	104.6	0	0.000	NP	0.000
5	green	104.5	0	0.000	NP	26.043
6	green	104.3	0	0.000	NP	0.000

Table B.12 (cont.)

1/30/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.3	0.1	0.950	113.1	71.221
2	black	104.4	0.1	0.958	108.7	19.700
3	black	103.9	0.1	0.962	117.9	95.464
4	green	104.6	0	0.000	62.1	0.000
5	green	104.5	0	0.000	75.1	26.043
6	green	104.3	0	0.000	44.7	0.000

2/6/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.3	0.4	3.799	123.2	72.657
2	black	104.4	0.1	0.958	90.1	20.279
3	black	103.9	0.4	3.850	135.0	96.920
4	green	104.6	0	0.000	49.6	0.000
5	green	104.5	0.1	0.957	77.3	26.332
6	green	104.3	0	0.000	37.7	0.000

2/13/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.3	0.3	2.849	116.4	74.667
2	black	104.4	0.2	1.916	107.1	21.148
3	black	103.9	0.5	4.812	149.5	99.539
4	green	104.6	0	0.000	45.3	0.000
5	green	104.5	0	0.000	75.9	26.621
6	green	104.3	0	0.000	35.3	0.000

2/20/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.3	1.2	11.396	NP	78.975
2	black	104.4	0.3	2.874	NP	22.597
3	black	103.9	0.9	8.662	NP	103.613
4	green	104.6	0	0.000	NP	0.000
5	green	104.5	0.1	0.957	NP	26.911
6	green	104.3	0.1	0.959	NP	0.290

Table B.12 (cont.)

2/27/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.3	0.4	3.799	139.5	83.570
2	black	104.4	0.1	0.958	121.0	23.755
3	black	103.9	0.9	8.662	194.0	108.852
4	green	104.6	0	0.000	64.4	0.000
5	green	104.5	0	0.000	75.6	27.200
6	green	104.3	0	0.000	45.0	0.580

3/5/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.3	1	9.497	153.1	87.591
2	black	104.4	0.5	4.789	132.6	25.493
3	black	103.9	4.9	47.161	283.7	125.733
4	green	104.6	0	0.000	49.6	0.000
5	green	104.5	0.2	1.914	97.0	27.779
6	green	104.3	0	0.000	38.1	0.580

3/12/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.3	1.1	10.446	154.0	93.622
2	black	104.4	0.3	2.874	108.3	27.811
3	black	103.9	4.7	45.236	262.9	153.674
4	green	104.6	0	0.000	45.3	0.000
5	green	104.5	0	0.000	66.3	28.358
6	green	104.3	0	0.000	35.2	0.580

3/19/2004

Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.3	0.7	6.648	NP	98.791
2	black	104.4	0.3	2.874	NP	29.549
3	black	103.9	2.9	27.911	NP	175.794
4	green	104.6	0	0.000	NP	0.000
5	green	104.5	0	0.000	NP	28.358
6	green	104.3	0	0.000	NP	0.580

Table B.12 (cont.)

3/26/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.3	0.4	3.799	134.4	99.652
2	black	104.4	0	0.000	94.5	28.100
3	black	103.9	1.6	15.399	224.9	180.159
4	green	104.6	0	0.000	64.2	0.000
5	green	104.5	0	0.000	73.8	28.358
6	green	104.3	0	0.000	47.9	0.580
4/2/2004						
Specimen	Bar	Resistor (ohms)	Voltage (mV)	Current (10-6 Amp)	Corrosion Potential (mV)	Total Corrosion (Coulombs)
1	black	105.3	0.1	0.950	87.6	101.088
2	black	104.4	0.4	3.831	128.6	29.259
3	black	103.9	2.9	27.911	255.4	193.256
4	green	104.6	0	0.000	46.6	0.000
5	green	104.5	0	0.000	85.3	28.358
6	green	104.3	0	0.000	37.0	0.580

APPENDIX C – DATA RECORD OF TENSION TESTS OF REINFORCING BARS

Table C.1: Data Record of Black Steel Tension Test 1 (Extensometer Setup)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.00739	0.00671	0.14	0.00009	0.00004
0.00789	0.00923	0.19	0.00010	0.00005
0.00856	0.01175	0.24	0.00013	0.00006
0.00906	0.01511	0.31	0.00016	0.00008
0.00940	0.01679	0.34	0.00013	0.00007
0.00990	0.01930	0.39	0.00017	0.00009
0.01057	0.02182	0.44	0.00021	0.00011
0.01091	0.02518	0.51	0.00013	0.00007
0.01158	0.02602	0.53	0.00009	0.00005
0.01225	0.02937	0.60	0.00017	0.00009
0.01259	0.03189	0.65	0.00017	0.00009
0.01326	0.03273	0.67	0.00023	0.00012
0.01360	0.03441	0.70	0.00016	0.00008
0.01444	0.04028	0.82	0.00026	0.00013
0.01494	0.04616	0.94	0.00019	0.00010
0.01527	0.05203	1.06	0.00026	0.00013
0.01578	0.05707	1.16	0.00026	0.00013
0.01628	0.06378	1.30	0.00040	0.00020
0.01662	0.07134	1.45	0.00032	0.00016
0.01729	0.07469	1.52	0.00026	0.00013
0.01779	0.08393	1.71	0.00017	0.00008
0.01830	0.09316	1.90	0.00026	0.00013
0.01897	0.09987	2.03	0.00026	0.00013
0.01947	0.11078	2.26	0.00028	0.00014
0.02014	0.12001	2.44	0.00028	0.00014
0.02065	0.13092	2.67	0.00027	0.00013
0.02065	0.14939	3.04	0.00031	0.00015
0.02132	0.17541	3.57	0.00034	0.00017
0.02199	0.20394	4.15	0.00042	0.00021
0.02300	0.22828	4.65	0.00042	0.00021
0.02283	0.25765	5.25	0.00047	0.00023

Table C.1 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.02350	0.29038	5.92	0.00053	0.00027
0.02400	0.31724	6.46	0.00062	0.00031
0.02484	0.35585	7.25	0.00068	0.00034
0.02501	0.38438	7.83	0.00070	0.00035
0.02551	0.41963	8.55	0.00079	0.00039
0.02635	0.45152	9.20	0.00087	0.00044
0.02669	0.48341	9.85	0.00088	0.00044
0.02719	0.51782	10.55	0.00091	0.00046
0.02786	0.56063	11.42	0.00101	0.00051
0.02820	0.59000	12.02	0.00105	0.00052
0.02887	0.62441	12.72	0.00111	0.00056
0.02921	0.65798	13.40	0.00119	0.00059
0.02988	0.69659	14.19	0.00125	0.00062
0.03055	0.73519	14.98	0.00130	0.00065
0.03088	0.76540	15.59	0.00134	0.00067
0.03156	0.79897	16.28	0.00140	0.00070
0.03223	0.84178	17.15	0.00148	0.00074
0.03240	0.87703	17.87	0.00152	0.00076
0.03307	0.91899	18.72	0.00156	0.00078
0.03357	0.95424	19.44	0.00164	0.00082
0.03407	0.99452	20.26	0.00172	0.00086
0.03475	1.03481	21.08	0.00176	0.00088
0.03508	1.07006	21.80	0.00182	0.00091
0.03558	1.10530	22.52	0.00189	0.00095
0.03626	1.14811	23.39	0.00195	0.00097
0.03659	1.18419	24.12	0.00200	0.00100
0.03710	1.22868	25.03	0.00206	0.00103
0.03777	1.26980	25.87	0.00214	0.00107
0.03844	1.30924	26.67	0.00224	0.00112
0.03877	1.35289	27.56	0.00224	0.00112
0.03928	1.39149	28.35	0.00232	0.00116
0.03995	1.43345	29.20	0.00238	0.00119
0.04045	1.47710	30.09	0.00245	0.00123

Table C.1 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.04096	1.51990	30.96	0.00256	0.00128
0.04129	1.55850	31.75	0.00257	0.00129
0.04196	1.59879	32.57	0.00266	0.00133
0.04230	1.63236	33.25	0.00270	0.00135
0.04314	1.67348	34.09	0.00277	0.00139
0.04347	1.71880	35.02	0.00285	0.00143
0.04415	1.76328	35.92	0.00290	0.00145
0.04448	1.80357	36.74	0.00295	0.00147
0.04498	1.84050	37.49	0.00301	0.00151
0.04599	1.88246	38.35	0.00307	0.00153
0.04633	1.92274	39.17	0.00312	0.00156
0.04666	1.96303	39.99	0.00322	0.00161
0.04717	2.00247	40.79	0.00323	0.00161
0.04750	2.03940	41.55	0.00334	0.00167
0.04817	2.08136	42.40	0.00336	0.00168
0.04851	2.12165	43.22	0.00346	0.00173
0.04918	2.16781	44.16	0.00352	0.00176
0.04952	2.20725	44.97	0.00359	0.00179
0.05019	2.25173	45.87	0.00363	0.00182
0.05086	2.29034	46.66	0.00371	0.00186
0.05119	2.33734	47.62	0.00375	0.00187
0.05187	2.38098	48.50	0.00387	0.00193
0.05254	2.42966	49.50	0.00393	0.00197
0.05321	2.46574	50.23	0.00397	0.00199
0.05338	2.51610	51.26	0.00403	0.00201
0.05405	2.55303	52.01	0.00412	0.00206
0.05472	2.60506	53.07	0.00420	0.00210
0.05506	2.64786	53.94	0.00425	0.00213
0.05556	2.68479	54.69	0.00430	0.00215
0.05640	2.73263	55.67	0.00439	0.00220
0.05673	2.78047	56.64	0.00449	0.00224
0.05707	2.82662	57.58	0.00457	0.00228
0.05757	2.86355	58.34	0.00457	0.00228
0.05824	2.90300	59.14	0.00467	0.00233

Table C.1 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.05875	2.93405	59.77	0.00471	0.00236
0.05925	2.97853	60.68	0.00479	0.00239
0.05959	3.02469	61.62	0.00488	0.00244
0.06026	3.05658	62.27	0.00490	0.00245

Table C.2: Data Record for Black Steel Tension Test 2 (Extensometer Setup)

Axial Displacement of Actuator (in.)	Axial Force (kip.)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.01007	0.00252	0.05	0.00020	0.00010
0.01057	0.00168	0.03	0.00019	0.00009
0.01108	0.00336	0.07	0.00025	0.00012
0.01158	0.00504	0.10	0.00022	0.00011
0.01192	0.00839	0.17	0.00025	0.00012
0.01242	0.00923	0.19	0.00016	0.00008
0.01309	0.01343	0.27	0.00030	0.00015
0.01376	0.01511	0.31	0.00028	0.00014
0.01427	0.01595	0.32	0.00036	0.00018
0.01460	0.01930	0.39	0.00027	0.00013
0.01527	0.02350	0.48	0.00037	0.00018
0.01578	0.03105	0.63	0.00034	0.00017
0.01628	0.04364	0.89	0.00035	0.00017
0.01695	0.05959	1.21	0.00038	0.00019
0.01746	0.08141	1.66	0.00045	0.00022
0.01813	0.10910	2.22	0.00044	0.00022
0.01863	0.13764	2.80	0.00046	0.00023
0.01897	0.16701	3.40	0.00051	0.00026
0.01964	0.19219	3.92	0.00056	0.00028
0.01997	0.22156	4.51	0.00056	0.00028
0.02031	0.25513	5.20	0.00059	0.00030
0.02098	0.29290	5.97	0.00065	0.00033
0.02165	0.32144	6.55	0.00066	0.00033
0.02232	0.36004	7.33	0.00068	0.00034

Table C.2 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.02249	0.39277	8.00	0.00074	0.00037
0.02316	0.43054	8.77	0.00078	0.00039
0.02350	0.45824	9.34	0.00082	0.00041
0.02417	0.49852	10.16	0.00087	0.00044
0.02467	0.52789	10.75	0.00089	0.00045
0.02551	0.56314	11.47	0.00095	0.00048
0.02585	0.59923	12.21	0.00099	0.00049
0.02618	0.63532	12.94	0.00103	0.00052
0.02652	0.66553	13.56	0.00105	0.00053
0.02719	0.70582	14.38	0.00113	0.00056
0.02770	0.74107	15.10	0.00120	0.00060
0.02837	0.78051	15.90	0.00119	0.00059
0.02853	0.81828	16.67	0.00127	0.00063
0.02954	0.85940	17.51	0.00132	0.00066
0.03005	0.90388	18.41	0.00137	0.00068
0.03021	0.93242	19.00	0.00142	0.00071
0.03088	0.97438	19.85	0.00146	0.00073
0.03156	1.01802	20.74	0.00150	0.00075
0.03206	1.05411	21.47	0.00153	0.00077
0.03240	1.09523	22.31	0.00160	0.00080
0.03307	1.12880	23.00	0.00165	0.00083
0.03357	1.17664	23.97	0.00173	0.00087
0.03424	1.21357	24.72	0.00172	0.00086
0.03458	1.25973	25.66	0.00181	0.00091
0.03525	1.29498	26.38	0.00187	0.00094
0.03558	1.33610	27.22	0.00193	0.00097
0.03609	1.36883	27.89	0.00197	0.00099
0.03693	1.41415	28.81	0.00207	0.00104
0.03710	1.45360	29.61	0.00211	0.00105
0.03760	1.49472	30.45	0.00216	0.00108
0.03844	1.53752	31.32	0.00224	0.00112
0.03877	1.58032	32.19	0.00220	0.00110
0.03945	1.62397	33.08	0.00235	0.00117
0.03978	1.66173	33.85	0.00243	0.00122

Table C.2 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.04112	1.75153	35.68	0.00249	0.00125
0.04163	1.79685	36.61	0.00258	0.00129
0.04247	1.87407	38.18	0.00263	0.00132
0.04314	1.91939	39.10	0.00275	0.00137
0.04331	1.96135	39.96	0.00276	0.00138
0.04398	2.00079	40.76	0.00281	0.00140
0.04465	2.03856	41.53	0.00288	0.00144
0.04515	2.08556	42.49	0.00296	0.00148
0.04549	2.12416	43.27	0.00303	0.00152
0.04599	2.16277	44.06	0.00308	0.00154
0.04683	2.21061	45.03	0.00311	0.00155
0.04700	2.24921	45.82	0.00317	0.00158
0.04784	2.28950	46.64	0.00322	0.00161
0.04834	2.32055	47.27	0.00330	0.00165
0.04901	2.37426	48.37	0.00332	0.00166
0.04968	2.41371	49.17	0.00333	0.00167
0.04968	2.45483	50.01	0.00342	0.00171
0.05052	2.49596	50.85	0.00350	0.00175
0.05086	2.53960	51.74	0.00359	0.00180
0.05153	2.57736	52.51	0.00362	0.00181
0.05220	2.62268	53.43	0.00369	0.00185
0.05237	2.66549	54.30	0.00373	0.00187
0.05287	2.70493	55.10	0.00381	0.00191
0.05338	2.74354	55.89	0.00384	0.00192
0.05405	2.79305	56.90	0.00391	0.00196
0.05472	2.83334	57.72	0.00397	0.00199
0.05539	2.87530	58.58	0.00404	0.00202
0.05556	2.91726	59.43	0.00409	0.00204
0.05623	2.96175	60.34	0.00417	0.00208
0.05690	3.00287	61.17	0.00427	0.00214
0.05707	3.04064	61.94	0.00433	0.00217
0.05774	3.07756	62.70	0.00440	0.00220
0.05824	3.12288	63.62	0.00444	0.00222
0.05858	3.15645	64.30	0.00450	0.00225

Table C.3: Data Record of Black Steel Tension Test 3 (Extensometer Setup)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.00403	0.00084	0.02	0.00017	0.00009
0.00453	0.00168	0.03	0.00019	0.00009
0.00520	0.00420	0.09	0.00020	0.00010
0.00587	0.00420	0.09	0.00017	0.00009
0.00621	0.00923	0.19	0.00016	0.00008
0.00671	0.01259	0.26	0.00022	0.00011
0.00739	0.01343	0.27	0.00020	0.00010
0.00789	0.01679	0.34	0.00022	0.00011
0.00822	0.02518	0.51	0.00027	0.00013
0.00890	0.02937	0.60	0.00028	0.00014
0.00957	0.03777	0.77	0.00033	0.00016
0.00990	0.04700	0.96	0.00030	0.00015
0.01041	0.05539	1.13	0.00044	0.00022
0.01091	0.07050	1.44	0.00012	0.00006
0.01141	0.09316	1.90	0.00016	0.00008
0.01192	0.11834	2.41	0.00021	0.00010
0.01242	0.13932	2.84	0.00019	0.00009
0.01276	0.16366	3.33	0.00026	0.00013
0.01343	0.19807	4.03	0.00028	0.00014
0.01393	0.22744	4.63	0.00033	0.00016
0.01460	0.25597	5.21	0.00036	0.00018
0.01511	0.28871	5.88	0.00040	0.00020
0.01544	0.32060	6.53	0.00044	0.00022
0.01611	0.35165	7.16	0.00047	0.00023
0.01645	0.38690	7.88	0.00051	0.00026
0.01729	0.42467	8.65	0.00056	0.00028
0.01762	0.45236	9.22	0.00060	0.00030
0.01813	0.48929	9.97	0.00063	0.00032
0.01880	0.52034	10.60	0.00067	0.00034
0.01930	0.55979	11.40	0.00073	0.00036
0.01981	0.59839	12.19	0.00078	0.00039
0.02031	0.63196	12.87	0.00078	0.00039
0.02081	0.67057	13.66	0.00085	0.00043
0.02132	0.70162	14.29	0.00089	0.00044

Table C.3 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.02199	0.74358	15.15	0.00094	0.00047
0.02232	0.78387	15.97	0.00097	0.00048
0.02283	0.81996	16.70	0.00103	0.00052
0.02367	0.85940	17.51	0.00107	0.00053
0.02417	0.89465	18.23	0.00114	0.00057
0.02467	0.92738	18.89	0.00115	0.00058
0.02501	0.96515	19.66	0.00122	0.00061
0.02551	1.00879	20.55	0.00128	0.00064
0.02618	1.04404	21.27	0.00133	0.00066
0.02702	1.08768	22.16	0.00138	0.00069
0.02702	1.12880	23.00	0.00142	0.00071
0.02786	1.16825	23.80	0.00146	0.00073
0.02820	1.20937	24.64	0.00155	0.00078
0.02887	1.24798	25.42	0.00159	0.00080
0.02937	1.28574	26.19	0.00163	0.00082
0.02971	1.33274	27.15	0.00164	0.00082
0.03038	1.37722	28.06	0.00177	0.00088
0.03055	1.41583	28.84	0.00177	0.00089
0.03139	1.45695	29.68	0.00186	0.00093
0.03172	1.50479	30.66	0.00192	0.00096
0.03206	1.53165	31.20	0.00190	0.00095
0.03290	1.58368	32.26	0.00201	0.00101
0.03340	1.62145	33.03	0.00206	0.00103
0.03391	1.66677	33.96	0.00209	0.00104
0.03458	1.70454	34.72	0.00215	0.00107
0.03508	1.76160	35.89	0.00222	0.00111
0.03542	1.78678	36.40	0.00228	0.00114
0.03626	1.83462	37.37	0.00235	0.00117
0.03642	1.87574	38.21	0.00235	0.00117
0.03693	1.91939	39.10	0.00242	0.00121
0.03760	1.96722	40.08	0.00252	0.00126
0.03844	2.01086	40.96	0.00254	0.00127
0.03861	2.04695	41.70	0.00261	0.00130
0.03911	2.08724	42.52	0.00264	0.00132

Table C.3 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.03978	2.13088	43.41	0.00274	0.00137
0.04028	2.17620	44.33	0.00275	0.00138
0.04062	2.21900	45.21	0.00279	0.00139
0.04129	2.26684	46.18	0.00287	0.00143
0.04196	2.31552	47.17	0.00295	0.00148
0.04230	2.34741	47.82	0.00297	0.00148
0.04297	2.39357	48.76	0.00303	0.00152
0.04364	2.43133	49.53	0.00310	0.00155
0.04415	2.47497	50.42	0.00319	0.00159
0.04431	2.51946	51.33	0.00320	0.00160
0.04498	2.56310	52.21	0.00328	0.00164
0.04515	2.60590	53.09	0.00332	0.00166
0.04582	2.65038	53.99	0.00343	0.00172
0.04683	2.68983	54.80	0.00346	0.00173
0.04717	2.72675	55.55	0.00352	0.00176
0.04767	2.77627	56.56	0.00356	0.00178
0.04817	2.81152	57.28	0.00361	0.00180
0.04851	2.86523	58.37	0.00370	0.00185
0.04901	2.91139	59.31	0.00380	0.00190
0.04952	2.94328	59.96	0.00384	0.00192
0.05019	2.98776	60.87	0.00388	0.00194
0.05052	3.03056	61.74	0.00398	0.00199
0.05136	3.06330	62.40	0.00403	0.00201
0.05187	3.11197	63.40	0.00412	0.00206
0.05237	3.15226	64.22	0.00415	0.00207
0.05304	3.19842	65.16	0.00429	0.00215

Table C.4: Data Record of MMFX Steel Tension Test 1 (Extensometer Setup)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.01930	0.02686	0.55	0.00010	0.00005
0.02434	0.08225	1.68	0.00023	0.00011
0.02954	0.37851	7.71	0.00056	0.00028
0.03475	0.75198	15.32	0.00101	0.00051
0.03978	1.13887	23.20	0.00151	0.00076
0.04515	1.55347	31.65	0.00208	0.00104
0.05036	1.96974	40.13	0.00267	0.00134
0.05589	2.39021	48.69	0.00332	0.00166
0.06110	2.81320	57.31	0.00398	0.00199
0.06630	3.24038	66.01	0.00473	0.00236
0.07167	3.64742	74.30	0.00548	0.00274
0.07637	4.04271	82.36	0.00622	0.00311
0.08191	4.43464	90.34	0.00707	0.00353
0.08695	4.80392	97.86	0.00800	0.00400
0.09215	5.15137	104.94	0.00898	0.00449
0.09735	5.46609	111.35	0.00998	0.00499
0.10289	5.77075	117.56	0.01111	0.00556
0.10776	6.05106	123.27	0.01235	0.00617
0.11330	6.30871	128.52	0.01360	0.00680
0.11850	6.55713	133.58	0.01508	0.00754
0.12371	6.77198	137.96	0.01654	0.00827
0.12874	6.97760	142.15	0.01810	0.00905
0.13395	7.16140	145.89	0.01971	0.00985
0.13898	7.32086	149.14	0.02135	0.01068
0.14402	7.46269	152.03	0.02311	0.01155
0.14972	7.60536	154.94	0.02498	0.01249
0.15476	7.73042	157.48	0.02689	0.01344
0.15996	7.83448	159.60	0.02880	0.01440
0.16500	7.93771	161.71	0.03083	0.01542
0.17037	8.02499	163.48	0.03294	0.01647
0.17557	8.10892	165.19	0.03496	0.01748
0.18061	8.17438	166.53	0.03713	0.01856
0.18598	8.23733	167.81	0.03932	0.01966
0.19118	8.30447	169.18	0.04153	0.02076

Table C.4 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.19622	8.35650	170.24	0.04376	0.02188
0.20142	8.40686	171.26	0.04605	0.02303
0.20679	8.44798	172.10	0.04842	0.02421
0.21200	8.48575	172.87	0.05070	0.02535
0.22224	8.55037	174.19	0.05544	0.02772
0.22744	8.58226	174.84	0.05781	0.02890
0.23264	8.60576	175.32	0.06023	0.03011
0.23785	8.62842	175.78	0.06264	0.03132
0.24322	8.65612	176.34	0.06504	0.03252
0.24825	8.67039	176.63	0.06744	0.03372
0.25362	8.68717	176.97	0.06981	0.03490
0.25883	8.69976	177.23	0.07214	0.03607
0.26370	8.71990	177.64	0.07446	0.03723
0.26907	8.73753	178.00	0.07678	0.03839
0.27461	8.74004	178.05	0.07895	0.03948
0.27947	8.74256	178.10	0.08105	0.04053
0.28468	8.74424	178.14	0.08294	0.04147
0.29005	8.72997	177.85	0.08439	0.04219
0.29508	8.68381	176.91	0.08525	0.04262

Table C.5: Data Record of MMFX Steel Tension Test 2 (Extensometer Setup)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.00890	0.00168	0.03	0.00017	0.00009
0.01376	0.01091	0.22	0.00028	0.00014
0.01981	0.03525	0.72	0.00044	0.00022
0.02501	0.06127	1.25	0.00064	0.00032
0.03038	0.16869	3.44	0.00081	0.00041
0.03542	0.44816	9.13	0.00117	0.00058
0.04146	0.86108	17.54	0.00172	0.00086
0.04649	1.26141	25.70	0.00222	0.00111
0.05203	1.68523	34.33	0.00281	0.00140
0.05690	2.10067	42.79	0.00342	0.00171

Table C.5 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.06227	2.52365	51.41	0.00409	0.00204
0.06748	2.93069	59.70	0.00475	0.00238
0.07285	3.35116	68.27	0.00548	0.00274
0.07772	3.75065	76.41	0.00620	0.00310
0.08309	4.12496	84.03	0.00697	0.00348
0.08846	4.49004	91.47	0.00780	0.00390
0.09349	4.83833	98.57	0.00868	0.00434
0.09870	5.16144	105.15	0.00958	0.00479
0.10373	5.47616	111.56	0.01069	0.00534
0.10910	5.76823	117.51	0.01176	0.00588
0.11464	6.04350	123.12	0.01299	0.00649
0.11968	6.28857	128.11	0.01427	0.00714
0.12505	6.51685	132.76	0.01564	0.00782
0.13009	6.72330	136.97	0.01704	0.00852
0.13529	6.92305	141.04	0.01859	0.00930
0.14066	7.09761	144.59	0.02019	0.01009
0.14570	7.26379	147.98	0.02188	0.01094
0.15090	7.40898	150.93	0.02368	0.01184
0.15593	7.54578	153.72	0.02555	0.01277
0.16147	7.67922	156.44	0.02750	0.01375
0.16651	7.78497	158.59	0.02951	0.01475
0.17171	7.88148	160.56	0.03159	0.01579
0.17692	7.97128	162.39	0.03374	0.01687
0.18178	8.05773	164.15	0.03597	0.01799
0.18715	8.12822	165.59	0.03826	0.01913
0.19269	8.19201	166.89	0.04061	0.02030
0.19756	8.24992	168.07	0.04294	0.02147
0.20293	8.29859	169.06	0.04536	0.02268
0.21317	8.39259	170.97	0.05032	0.02516
0.21838	8.43455	171.83	0.05291	0.02646
0.22375	8.47064	172.56	0.05554	0.02777
0.22895	8.49750	173.11	0.05809	0.02905
0.23432	8.52771	173.73	0.06076	0.03038
0.23952	8.55709	174.32	0.06352	0.03176

Table C.5 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.24456	8.57639	174.72	0.06632	0.03316
0.24960	8.59569	175.11	0.06917	0.03458
0.25463	8.62087	175.62	0.07208	0.03604
0.26034	8.63262	175.86	0.07512	0.03756
0.26537	8.64773	176.17	0.07818	0.03909
0.27041	8.65948	176.41	0.08140	0.04070
0.27561	8.66451	176.51	0.08469	0.04234
0.28082	8.66619	176.55	0.08826	0.04413
0.28602	8.67122	176.65	0.09216	0.04608
0.29122	8.64689	176.15	0.09667	0.04834
0.29643	8.58310	174.85	0.10199	0.05100
0.30180	8.47568	172.67	0.10812	0.05406
0.30683	8.32293	169.55	0.11482	0.05741
0.31220	8.16515	166.34	0.12159	0.06080
0.31724	7.98471	162.66	0.12855	0.06427
0.32228	7.79336	158.77	0.13566	0.06783
0.32748	7.59110	154.64	0.14311	0.07155
0.33268	7.37457	150.23	0.15045	0.07522
0.33789	7.15720	145.81	0.15783	0.07892
0.34342	6.91046	140.78	0.16548	0.08274
0.34829	6.63602	135.19	0.17339	0.08670
0.35400	6.32801	128.91	0.18168	0.09084
0.35870	5.95035	121.22	0.19056	0.09528
0.36390	5.50974	112.24	0.20026	0.10013

Table C.6: Data Record of MMFX Steel Tension Test 3 (Extensometer Setup)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.00537	0.03525	0.72	0.00001	0.00001
0.01024	0.26353	5.37	0.00035	0.00017
0.01527	0.60930	12.41	0.00085	0.00042
0.02048	1.00459	20.47	0.00135	0.00067
0.02551	1.42422	29.01	0.00203	0.00101

Table C.6 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.03122	1.86148	37.92	0.00262	0.00131
0.03609	2.29453	46.74	0.00328	0.00164
0.04129	2.73347	55.69	0.00400	0.00200
0.04666	3.15561	64.29	0.00468	0.00234
0.05170	3.56769	72.68	0.00543	0.00272
0.05690	3.97893	81.06	0.00622	0.00311
0.06211	4.36583	88.94	0.00703	0.00351
0.06731	4.74097	96.58	0.00794	0.00397
0.07268	5.11528	104.21	0.00895	0.00447
0.07788	5.45602	111.15	0.01001	0.00501
0.08309	5.76067	117.36	0.01115	0.00557
0.08846	6.05441	123.34	0.01239	0.00620
0.09366	6.32466	128.84	0.01370	0.00685
0.09870	6.56804	133.80	0.01513	0.00756
0.10373	6.79128	138.35	0.01660	0.00830
0.10910	6.98431	142.28	0.01815	0.00908
0.11431	7.18070	146.28	0.01977	0.00988
0.11951	7.35443	149.82	0.02158	0.01079
0.12471	7.49878	152.76	0.02330	0.01165
0.12992	7.63306	155.50	0.02520	0.01260
0.13495	7.77154	158.32	0.02713	0.01357
0.14016	7.87225	160.37	0.02908	0.01454
0.14553	7.97464	162.46	0.03115	0.01558
0.15073	8.06528	164.30	0.03326	0.01663
0.15610	8.15592	166.15	0.03542	0.01771
0.16131	8.22306	167.52	0.03767	0.01884
0.16634	8.28433	168.77	0.03988	0.01994
0.17154	8.33888	169.88	0.04217	0.02109
0.17675	8.39595	171.04	0.04448	0.02224
0.18178	8.44882	172.12	0.04685	0.02343
0.18732	8.48071	172.77	0.04917	0.02459
0.19236	8.52184	173.61	0.05155	0.02578
0.19756	8.56464	174.48	0.05393	0.02696
0.20797	8.61751	175.55	0.05888	0.02944

Table C.6 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (kip)	Axial Stress (ksi)	Extensometer Displacement (in.)	Strain (in/in)
0.21300	8.65780	176.38	0.06145	0.03072
0.21838	8.67458	176.72	0.06396	0.03198
0.22324	8.70228	177.28	0.06655	0.03327
0.22878	8.71403	177.52	0.06901	0.03451
0.23382	8.73081	177.86	0.07161	0.03580
0.23902	8.75012	178.26	0.07417	0.03709
0.24422	8.76606	178.58	0.07680	0.03840
0.24943	8.77865	178.84	0.07943	0.03971
0.25480	8.77949	178.85	0.08208	0.04104
0.25983	8.78788	179.03	0.08475	0.04238
0.26487	8.79292	179.13	0.08746	0.04373
0.27024	8.79711	179.21	0.09018	0.04509

Table C.7 Data Record of Black Steel Tension Test 1 (LVDT Setup)

Axial Displacement of Actuator (in.)	Axial Force (in.)	Axial Stress (in.)	LVDT Displacement (in.)	Strain (in/in)
0.00000	-0.00504	-0.07	-0.00003	0.00000
0.00873	0.09316	1.32	-0.00094	-0.00012
0.01880	0.42131	5.96	-0.00010	-0.00001
0.02887	0.98697	13.96	0.00158	0.00020
0.03911	1.77755	25.15	0.00379	0.00047
0.04868	2.61597	37.01	0.00621	0.00078
0.05892	3.53160	49.96	0.00886	0.00111
0.06865	4.40024	62.25	0.01158	0.00145
0.07923	4.32890	61.24	0.02142	0.00268
0.08879	4.24078	59.99	0.03166	0.00396
0.09903	4.31295	61.02	0.04146	0.00518
0.10894	4.32051	61.12	0.05133	0.00642
0.11884	4.32638	61.21	0.06137	0.00767
0.12874	4.46738	63.20	0.07043	0.00880
0.13898	4.59830	65.05	0.07976	0.00997
0.14872	4.70908	66.62	0.08836	0.01104

Table C.7 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (in.)	Axial Stress (in.)	LVDT Displacement (in.)	Strain (in/in)
0.15896	4.80812	68.02	0.09715	0.01214
0.17876	4.99107	70.61	0.11431	0.01429
0.18883	5.08087	71.88	0.12310	0.01539
0.19890	5.14466	72.78	0.13160	0.01645
0.20864	5.20844	73.68	0.14002	0.01750
0.21871	5.28314	74.74	0.14878	0.01860
0.22878	5.34356	75.60	0.15751	0.01969
0.23885	5.41406	76.59	0.16617	0.02077
0.24892	5.46190	77.27	0.17494	0.02187
0.25866	5.51645	78.04	0.18370	0.02296
0.26890	5.56429	78.72	0.19249	0.02406
0.27880	5.61716	79.47	0.20136	0.02517
0.28887	5.65073	79.94	0.20975	0.02622
0.29878	5.69018	80.50	0.21787	0.02723
0.30868	5.73634	81.15	0.22667	0.02833
0.31875	5.76235	81.52	0.23499	0.02937
0.32882	5.78837	81.89	0.24386	0.03048
0.33872	5.82110	82.35	0.25245	0.03156
0.34863	5.85131	82.78	0.26091	0.03261
0.35887	5.88656	83.28	0.26957	0.03370
0.36894	5.90503	83.54	0.27826	0.03478
0.37901	5.92769	83.86	0.28696	0.03587
0.38908	5.95286	84.22	0.29579	0.03697
0.39898	5.98308	84.64	0.30485	0.03811
0.40855	5.99483	84.81	0.31365	0.03921
0.41896	6.01917	85.15	0.32251	0.04031
0.42886	6.03847	85.43	0.33154	0.04144
0.43876	6.05441	85.65	0.34054	0.04257
0.44900	6.06700	85.83	0.34960	0.04370
0.45907	6.08547	86.09	0.35863	0.04483
0.46881	6.09470	86.22	0.36736	0.04592
0.47871	6.11736	86.54	0.37646	0.04706
0.48878	6.11736	86.54	0.38552	0.04819
0.49869	6.13750	86.83	0.39462	0.04933

Table C.7 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (in.)	Axial Stress (in.)	LVDT Displacement (in.)	Strain (in/in)
0.50909	6.14254	86.90	0.40352	0.05044
0.51883	6.14757	86.97	0.41258	0.05157
0.52890	6.15764	87.11	0.42178	0.05272
0.53880	6.16771	87.26	0.43091	0.05386
0.54888	6.15680	87.10	0.43984	0.05498
0.55861	6.17359	87.34	0.44870	0.05609
0.56902	6.18702	87.53	0.45790	0.05724
0.57909	6.18366	87.48	0.46720	0.05840
0.58866	6.19709	87.67	0.47646	0.05956
0.59906	6.19961	87.71	0.48563	0.06070
0.60897	6.20632	87.80	0.49520	0.06190
0.61904	6.20464	87.78	0.50470	0.06309
0.62894	6.21303	87.90	0.51406	0.06426
0.63884	6.20380	87.77	0.52360	0.06545
0.64892	6.20884	87.84	0.53313	0.06664
0.65882	6.19961	87.71	0.54287	0.06786
0.66889	6.19877	87.69	0.55233	0.06904
0.67896	6.19373	87.62	0.56180	0.07023
0.68870	6.19205	87.60	0.57170	0.07146
0.69893	6.17443	87.35	0.58167	0.07271
0.70884	6.15848	87.12	0.59141	0.07393
0.71874	6.13414	86.78	0.60151	0.07519
0.72898	6.09302	86.20	0.61155	0.07644
0.73888	6.03679	85.40	0.62226	0.07778
0.74879	5.94951	84.17	0.63240	0.07905
0.75886	5.85719	82.86	0.64284	0.08035
0.76876	5.73550	81.14	0.65351	0.08169
0.77866	5.59954	79.22	0.66439	0.08305
0.78874	5.43168	76.84	0.67540	0.08443
0.79881	5.23194	74.02	0.68641	0.08580
0.80871	4.99611	70.68	0.69816	0.08727
0.81895	4.68558	66.29	0.71015	0.08877

Table C.8 Data Record of Black Steel Tension Test 2 (LVDT Setup)

Axial Displacement of Actuator (in.)	Axial Force (in.)	Axial Stress (in.)	LVDT Displacement (in.)	Strain (in/in)
0.00017	0.00587	0.08	-0.00010	-0.00001
0.00890	0.17541	2.48	-0.00305	-0.00038
0.01914	0.72344	10.23	-0.00282	-0.00035
0.02870	1.46619	20.74	-0.00111	-0.00014
0.03911	2.32055	32.83	0.00091	0.00011
0.04884	3.25549	46.06	0.00342	0.00043
0.05875	4.17280	59.03	0.00611	0.00076
0.06882	4.22483	59.77	0.01484	0.00185
0.07889	4.33813	61.37	0.02387	0.00298
0.08879	4.29617	60.78	0.03387	0.00423
0.09886	4.31463	61.04	0.04354	0.00544
0.10860	4.32134	61.13	0.05334	0.00667
0.11850	4.40024	62.25	0.06291	0.00786
0.12857	4.50430	63.72	0.07211	0.00901
0.13881	4.64278	65.68	0.08124	0.01016
0.14872	4.74349	67.11	0.09017	0.01127
0.15862	4.84252	68.51	0.09923	0.01240
0.17859	5.02297	71.06	0.11753	0.01469
0.18883	5.11109	72.31	0.12659	0.01582
0.19890	5.18746	73.39	0.13576	0.01697
0.20898	5.26635	74.50	0.14509	0.01814
0.21871	5.32006	75.26	0.15439	0.01930
0.22878	5.37713	76.07	0.16369	0.02046
0.23885	5.43840	76.94	0.17279	0.02160
0.24876	5.49127	77.69	0.18195	0.02274
0.25883	5.53743	78.34	0.19102	0.02388
0.26890	5.58359	78.99	0.20018	0.02502
0.27863	5.62471	79.57	0.20931	0.02616
0.28887	5.66332	80.12	0.21848	0.02731
0.29878	5.70444	80.70	0.22777	0.02847
0.30851	5.73718	81.16	0.23734	0.02967
0.31875	5.78501	81.84	0.24671	0.03084
0.32882	5.79928	82.04	0.25611	0.03201
0.33889	5.83705	82.58	0.26544	0.03318

Table C.8 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (in.)	Axial Stress (in.)	LVDT Displacement (in.)	Strain (in/in)
0.34896	5.87565	83.12	0.27481	0.03435
0.35887	5.88656	83.28	0.28404	0.03550
0.36860	5.90754	83.57	0.29347	0.03668
0.37884	5.93104	83.91	0.30294	0.03787
0.38874	5.94951	84.17	0.31220	0.03903
0.39898	5.97301	84.50	0.32160	0.04020
0.40872	5.99399	84.80	0.33097	0.04137
0.41879	6.00238	84.92	0.34044	0.04255
0.42853	6.01833	85.14	0.34987	0.04373
0.43860	6.04015	85.45	0.35907	0.04488
0.44884	6.04602	85.53	0.36696	0.04587
0.45874	6.05274	85.63	0.37632	0.04704
0.46881	6.06952	85.87	0.38569	0.04821
0.47855	6.07791	85.98	0.39512	0.04939
0.48878	6.09554	86.23	0.40466	0.05058
0.49869	6.09638	86.25	0.41433	0.05179
0.50876	6.10645	86.39	0.42379	0.05297
0.51866	6.11568	86.52	0.43326	0.05416
0.52890	6.11904	86.57	0.44252	0.05532
0.53864	6.12659	86.67	0.45159	0.05645
0.54871	6.12911	86.71	0.46099	0.05762
0.55878	6.13582	86.80	0.47076	0.05884
0.56868	6.14170	86.89	0.48032	0.06004
0.57892	6.14254	86.90	0.49003	0.06125
0.58866	6.14338	86.91	0.49980	0.06247
0.59873	6.13666	86.82	0.50940	0.06367
0.60863	6.13498	86.79	0.51913	0.06489
0.61870	6.13666	86.82	0.52904	0.06613
0.62877	6.13330	86.77	0.53877	0.06735
0.63851	6.10813	86.41	0.54851	0.06856
0.64875	6.09470	86.22	0.55854	0.06982
0.65899	6.05190	85.62	0.56855	0.07107
0.66872	6.00658	84.98	0.57882	0.07235
0.67862	5.93356	83.94	0.58933	0.07367

Table C.8 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (in.)	Axial Stress (in.)	LVDT Displacement (in.)	Strain (in/in)
0.68870	5.84040	82.62	0.59967	0.07496
0.69877	5.72878	81.05	0.61044	0.07631
0.70867	5.59534	79.16	0.62115	0.07764
0.71841	5.42077	76.69	0.63216	0.07902
0.72864	5.23194	74.02	0.64338	0.08042
0.73872	5.00786	70.85	0.65466	0.08183
0.74895	4.71915	66.76	0.66651	0.08331

Table C.9 Data Record of Black Steel Tension Test 3 (LVDT Setup)

Axial Displacement of Actuator (in.)	Axial Force (in.)	Axial Stress (in.)	LVDT Displacement (in.)	Strain (in/in)
0.00034	-0.00084	-0.01	-0.00010	-0.00001
0.00856	0.00336	0.05	0.00020	0.00003
0.01880	0.02434	0.34	0.00205	0.00026
0.02887	0.05371	0.76	0.00352	0.00044
0.03877	0.13344	1.89	0.00363	0.00045
0.04901	0.64119	9.07	0.00423	0.00053
0.05892	1.45444	20.58	0.00591	0.00074
0.06899	2.36839	33.51	0.00829	0.00104
0.07889	3.25968	46.12	0.01068	0.00133
0.08863	4.16440	58.91	0.01333	0.00167
0.09886	4.26092	60.28	0.02189	0.00274
0.10860	4.23322	59.89	0.03159	0.00395
0.11884	4.23826	59.96	0.04169	0.00521
0.12857	4.28274	60.59	0.05146	0.00643
0.13865	4.34568	61.48	0.06106	0.00763
0.14872	4.37590	61.91	0.07140	0.00893
0.15862	4.48752	63.49	0.08101	0.01013
0.17893	4.72083	66.79	0.09964	0.01245
0.18883	4.81735	68.15	0.10890	0.01361
0.19874	4.90463	69.39	0.11790	0.01474
0.20898	4.99863	70.72	0.12716	0.01590

Table C.9 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (in.)	Axial Stress (in.)	LVDT Displacement (in.)	Strain (in/in)
0.21871	5.07500	71.80	0.13626	0.01703
0.22878	5.15137	72.88	0.14556	0.01820
0.23852	5.21432	73.77	0.15489	0.01936
0.24876	5.27978	74.69	0.16423	0.02053
0.25883	5.33769	75.51	0.17329	0.02166
0.26890	5.39644	76.34	0.18286	0.02286
0.27897	5.44595	77.04	0.19206	0.02401
0.28887	5.50554	77.89	0.20139	0.02517
0.29878	5.53995	78.37	0.21035	0.02629
0.30902	5.59114	79.10	0.21968	0.02746
0.31875	5.62304	79.55	0.22892	0.02861
0.32865	5.66164	80.10	0.23828	0.02979
0.33856	5.69857	80.62	0.24765	0.03096
0.34863	5.73046	81.07	0.25678	0.03210
0.35887	5.77158	81.65	0.26621	0.03328
0.36911	5.78669	81.86	0.27541	0.03443
0.37884	5.81690	82.29	0.28461	0.03558
0.38874	5.83705	82.58	0.29374	0.03672
0.39882	5.86558	82.98	0.30264	0.03783
0.40889	5.88153	83.21	0.31187	0.03898
0.41862	5.91594	83.69	0.32130	0.04016
0.42869	5.92433	83.81	0.33047	0.04131
0.43876	5.95706	84.28	0.34007	0.04251
0.44884	5.95874	84.30	0.34953	0.04369
0.45891	5.97133	84.48	0.35897	0.04487
0.46881	5.98811	84.71	0.36857	0.04607
0.47888	6.00238	84.92	0.37804	0.04725
0.48878	6.01413	85.08	0.38754	0.04844
0.49886	6.02336	85.21	0.39717	0.04965
0.50876	6.03092	85.32	0.40667	0.05083
0.51849	6.05441	85.65	0.41647	0.05206
0.52873	6.05190	85.62	0.42607	0.05326
0.53880	6.07120	85.89	0.43554	0.05444
0.54871	6.07372	85.93	0.44504	0.05563

Table C.9 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (in.)	Axial Stress (in.)	LVDT Displacement (in.)	Strain (in/in)
0.55861	6.07204	85.90	0.45464	0.05683
0.56868	6.07372	85.93	0.46431	0.05804
0.57892	6.08715	86.12	0.47391	0.05924
0.58866	6.08463	86.08	0.48361	0.06045
0.59856	6.08882	86.14	0.49318	0.06165
0.60863	6.08715	86.12	0.50298	0.06287
0.61870	6.08631	86.10	0.51272	0.06409
0.62861	6.08295	86.06	0.52252	0.06532
0.63851	6.07707	85.97	0.53222	0.06653
0.64892	6.07624	85.96	0.54199	0.06775
0.65865	6.06365	85.78	0.55206	0.06901
0.66855	6.03595	85.39	0.56183	0.07023
0.67879	6.01245	85.06	0.57177	0.07147
0.68870	5.96377	84.37	0.58204	0.07276
0.69877	5.90671	83.56	0.59228	0.07404
0.70884	5.82782	82.45	0.60255	0.07532
0.71841	5.72291	80.96	0.61316	0.07665
0.72864	5.60625	79.31	0.62391	0.07799
0.73872	5.47533	77.46	0.63465	0.07933
0.74895	5.30496	75.05	0.64566	0.08071
0.75869	5.10353	72.20	0.65684	0.08210
0.76859	4.87106	68.91	0.66825	0.08353

Table C.10 Data Record of MMFX Steel Tension Test 1 (LVDT Setup)

Axial Displacement of Actuator (in.)	Axial Force (in.)	Axial Stress (in.)	LVDT Displacement (in.)	Strain (in/in)
0.00067	0.00420	0.06	0.00003	0.00000
0.00890	0.00336	0.05	-0.00037	-0.00005
0.01914	0.00420	0.06	-0.00081	-0.00010
0.02904	0.07721	1.09	0.00141	0.00018
0.03928	0.21233	3.00	0.00363	0.00045
0.04918	0.56902	8.05	0.00490	0.00061
0.05908	1.23707	17.50	0.00678	0.00085
0.06899	2.08136	29.45	0.00957	0.00120
0.07923	2.97769	42.13	0.01259	0.00157
0.08930	3.87570	54.83	0.01568	0.00196
0.09920	4.76531	67.42	0.01903	0.00238
0.10927	5.59534	79.16	0.02256	0.00282
0.11934	6.37165	90.14	0.02615	0.00327
0.12925	7.08251	100.20	0.03008	0.00376
0.13915	7.72034	109.22	0.03424	0.00428
0.14905	8.31874	117.69	0.03881	0.00485
0.15912	8.84159	125.08	0.04361	0.00545
0.17910	9.74799	137.91	0.05405	0.00676
0.18917	10.12902	143.30	0.05942	0.00743
0.19907	10.46640	148.07	0.06516	0.00815
0.20914	10.77189	152.39	0.07154	0.00894
0.21905	11.04549	156.26	0.07755	0.00969
0.22895	11.28636	159.67	0.08413	0.01052
0.23902	11.50037	162.70	0.09094	0.01137
0.24909	11.66067	164.96	0.09772	0.01222
0.25916	11.83859	167.48	0.10518	0.01315
0.26923	11.97455	169.41	0.11270	0.01409
0.27914	12.09288	171.08	0.12042	0.01505
0.28887	12.21458	172.80	0.12837	0.01605
0.29911	12.30857	174.13	0.13643	0.01705
0.30885	12.37823	175.12	0.14499	0.01812
0.31925	12.46216	176.30	0.15345	0.01918
0.32899	12.52175	177.15	0.16208	0.02026
0.33906	12.57042	177.84	0.17064	0.02133

Table C.10 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (in.)	Axial Stress (in.)	LVDT Displacement (in.)	Strain (in/in)
0.34896	12.62246	178.57	0.17980	0.02248
0.35920	12.65687	179.06	0.18870	0.02359
0.36894	12.66778	179.21	0.19786	0.02473
0.37884	12.70303	179.71	0.20713	0.02589
0.38925	12.69967	179.66	0.21666	0.02708
0.39898	12.60651	178.35	0.22690	0.02836
0.40922	12.34466	174.64	0.23842	0.02980
0.41929	11.98966	169.62	0.25037	0.03130
0.42903	11.59520	164.04	0.26276	0.03284
0.43910	11.12186	157.34	0.27581	0.03448
0.44900	10.60404	150.02	0.28881	0.03610
0.45891	9.97375	141.10	0.30297	0.03787
0.46881	9.21590	130.38	0.31761	0.03970
0.47905	8.15592	115.38	0.33550	0.04194

Table C.11 Data Record of MMFX Steel Tension Test 2 (LVDT Setup)

Axial Displacement of Actuator (in.)	Axial Force (in.)	Axial Stress (in.)	LVDT Displacement (in.)	Strain (in/in)
0.00050	0.00084	0.01	-0.00010	-0.00001
0.00890	0.00168	0.02	-0.00007	-0.00001
0.01930	0.01007	0.14	-0.00020	-0.00003
0.02904	0.03693	0.52	0.00007	0.00001
0.03911	0.10743	1.52	0.00067	0.00008
0.04901	0.52789	7.47	0.00211	0.00026
0.05908	1.19007	16.84	0.00369	0.00046
0.06915	1.99156	28.17	0.00618	0.00077
0.07923	2.86187	40.49	0.00906	0.00113
0.08913	3.72379	52.68	0.01202	0.00150
0.09920	4.57396	64.71	0.01497	0.00187
0.10910	5.41238	76.57	0.01826	0.00228
0.11934	6.21220	87.88	0.02182	0.00273
0.12925	6.94151	98.20	0.02575	0.00322

Table C.11 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (in.)	Axial Stress (in.)	LVDT Displacement (in.)	Strain (in/in)
0.13915	7.61292	107.70	0.02961	0.00370
0.14922	8.23229	116.46	0.03414	0.00427
0.15912	8.78368	124.26	0.03891	0.00486
0.17927	9.71778	137.48	0.04938	0.00617
0.18900	10.10300	142.93	0.05499	0.00687
0.19907	10.45465	147.90	0.06076	0.00760
0.20898	10.76182	152.25	0.06684	0.00835
0.21905	11.03542	156.12	0.07332	0.00916
0.22929	11.26873	159.42	0.07986	0.00998
0.23885	11.47855	162.39	0.08685	0.01086
0.24909	11.66738	165.06	0.09423	0.01178
0.25916	11.81845	167.20	0.10175	0.01272
0.26907	11.95692	169.16	0.10951	0.01369
0.27931	12.06771	170.72	0.11723	0.01465
0.28904	12.16758	172.14	0.12535	0.01567
0.29911	12.26325	173.49	0.13381	0.01673
0.30935	12.33879	174.56	0.14227	0.01778
0.31909	12.39753	175.39	0.15097	0.01887
0.32882	12.45712	176.23	0.15983	0.01998
0.33940	12.48901	176.68	0.16893	0.02112
0.34896	12.50496	176.91	0.17816	0.02227
0.35887	12.47391	176.47	0.18779	0.02347
0.36894	12.28675	173.82	0.19887	0.02486
0.37918	11.95441	169.12	0.21062	0.02633
0.38908	11.56751	163.65	0.22257	0.02782
0.39898	11.13949	157.59	0.23540	0.02942
0.40905	10.63761	150.49	0.24852	0.03107
0.41913	10.06440	142.38	0.26229	0.03279
0.42920	9.34935	132.27	0.27689	0.03461
0.43893	8.39763	118.80	0.29340	0.03668

Table C.12 Data Record of MMFX Steel Tension Test 3 (LVDT Setup)

Axial Displacement of Actuator (in.)	Axial Force (in.)	Axial Stress (in.)	LVDT Displacement (in.)	Strain (in/in)
0.00034	0.00587	0.08	0.00007	0.00001
0.00906	0.01091	0.15	0.00034	0.00004
0.01914	0.04868	0.69	-0.00077	-0.00010
0.02921	0.36508	5.16	-0.00020	-0.00003
0.03911	0.90052	12.74	0.00128	0.00016
0.04901	1.65334	23.39	0.00349	0.00044
0.05925	2.50183	35.39	0.00608	0.00076
0.06932	3.38809	47.93	0.00880	0.00110
0.07906	4.28777	60.66	0.01162	0.00145
0.08930	5.12535	72.51	0.01450	0.00181
0.09937	5.96377	84.37	0.01809	0.00226
0.10927	6.75268	95.53	0.02112	0.00264
0.11917	7.45850	105.52	0.02484	0.00311
0.12891	8.11647	114.82	0.02884	0.00360
0.13898	8.70060	123.09	0.03313	0.00414
0.14922	9.21003	130.30	0.03773	0.00472
0.15912	9.66994	136.80	0.04243	0.00530
0.17910	10.48654	148.35	0.05244	0.00655
0.18934	10.82980	153.21	0.05774	0.00722
0.19890	11.11850	157.29	0.06308	0.00788
0.20914	11.40217	161.31	0.06902	0.00863
0.21905	11.64052	164.68	0.07506	0.00938
0.22912	11.86964	167.92	0.08141	0.01018
0.23902	12.04505	170.40	0.08785	0.01098
0.24943	12.21877	172.86	0.09474	0.01184
0.25900	12.37320	175.04	0.10192	0.01274
0.26923	12.49825	176.81	0.10941	0.01368
0.27947	12.63505	178.75	0.11706	0.01463
0.28904	12.72904	180.08	0.12481	0.01560
0.29894	12.81884	181.35	0.13294	0.01662
0.30885	12.89605	182.44	0.14123	0.01765
0.31909	12.96487	183.42	0.14969	0.01871
0.32916	13.01943	184.19	0.15832	0.01979
0.33906	13.07398	184.96	0.16731	0.02091

Table C.12 (cont.)

Axial Displacement of Actuator (in.)	Axial Force (in.)	Axial Stress (in.)	LVDT Displacement (in.)	Strain (in/in)
0.34913	13.09748	185.29	0.17631	0.02204
0.35887	13.11510	185.54	0.18544	0.02318
0.36911	13.08657	185.14	0.19514	0.02439
0.37935	12.92459	182.85	0.20592	0.02574
0.38891	12.64428	178.88	0.21767	0.02721
0.39898	12.28088	173.74	0.23002	0.02875
0.40905	11.87300	167.97	0.24271	0.03034
0.41913	11.40637	161.37	0.25564	0.03195
0.42886	10.87092	153.79	0.26910	0.03364
0.43893	10.23057	144.73	0.28300	0.03537
0.44900	9.42908	133.39413	0.29834	0.03729
0.45891	8.30531	117.49606	0.31596	0.03950

APPENDIX D – DATA RECORD OF ASTM C 1202 TESTS

Table D.1 Data Record of ASTM C 1202 Test of Cores A4 and A6 from Northbound Bridge Over Chikaskia River on I-35, Kay County, Oklahoma

	Core A4		**Core A6**		**Average**	
Time (minutes)	Current (mA)	Charge passed (coulombs)	Current (mA)	Charge passed (coulombs)	Current (mA)	Charge passed (coulombs)
1	99	6	86	5	92.5	5.5
30	129	196	95	163	112	179.5
60	119	404	105	345	112	374.5
90	129	628	113	543	121	585.5
120	138	870	120	755	129	812.5
150	147	1127	126	978	136.5	1052.5
180	153	1397	130	1208	141.5	1302.5
210	159	1679	134	1446	146.5	1562.5
240	163	1969	137	1691	150	1830
270	165	2264	139	1940	152	2102
300	165	2562	139	2192	152	2377
330	163	2858	136	2441	149.5	2649.5
360	161	3152	131	2683	146	2917.5

Table D.2 Data Record of ASTM C 1202 Test of Cores B4 and B6 from Northbound Bridge Over Chikaskia River on I-35, Kay County, Oklahoma

	Core B4		Core B6		Average	
Time (minutes)	Current (mA)	Charge passed (coulombs)	Current (mA)	Charge passed (coulombs)	Current (mA)	Charge passed (coulombs)
1	75	4	94	5	84.5	4.5
30	84	144	103	178	93.5	161
60	89	302	112	372	100.5	337
90	94	468	120	582	107	525
120	98	642	127	805	112.5	723.5
150	101	822	132	1039	116.5	930.5
180	104	1009	136	1282	120	1145.5
210	105	1199	138	1529	121.5	1364
240	106	1391	138	1780	122	1585.5
270	107	1584	137	2029	122	1806.5
300	106	1777	134	2275	120	2026
330	105	1968	129	2513	117	2240.5
360	105	2158	122	2741	113.5	2449.5

Table D.3 Statistical Analysis of ASTM C 1202 Tests of Group A and B Cores

	Group A & B Average		Standard Deviation
Time (minutes)	Current (mA)	Charge passed (coulombs)	Charge passed (coulombs)
1	88.5	5	0.8
30	102.75	170.25	22.1
60	106.25	355.75	43.2
90	114	555.25	67.8
120	120.75	768	96.3
150	126.5	991.5	128.5
180	130.75	1224	163.1
210	134	1463.25	200.8
240	136	1707.75	240.9
270	137	1954.25	282.1
300	136	2201.5	324.4
330	133.25	2445	366.4
360	129.75	2683.5	407.8

Table D.4 Data Record of ASTM C 1202 Test of Cores E4 and E6 from Southbound Bridge Over Chikaskia River on I-35, Kay County, Oklahoma

	Core E4		Core E6		Average	
Time (minutes)	Current (mA)	Charge passed (coulombs)	Current (mA)	Charge passed (coulombs)	Current (mA)	Charge passed (coulombs)
1	71	4	64	3	67.5	3.5
30	77	134	69	120	73	127
60	84	280	73	249	78.5	264.5
90	90	437	76	383	83	410
120	95	604	78	523	86.5	563.5
150	99	780	80	665	89.5	722.5
180	103	963	82	815	92.5	889
210	106	1153	83	965	94.5	1059
240	108	1347	84	1116	96	1231.5
270	110	1545	84	1268	97	1406.5
300	111	1746	83	1419	97	1582.5
330	111	1947	83	1569	97	1758
360	111	2148	82	1718	96.5	1933

Table D.5 Data Record of ASTM C 1202 Test of Cores F4 and F6 from Southbound Bridge Over Chikaskia River on I-35, Kay County, Oklahoma

	Core F4		Core F6		Average	
Time (minutes)	Current (mA)	Charge passed (coulombs)	Current (mA)	Charge passed (coulombs)	Current (mA)	Charge passed (coulombs)
1	61	3	59	3	60	3
30	72	115	68	116	70	115.5
60	70	243	74	245	72	244
90	76	376	80	385	78	380.5
120	80	517	85	535	82.5	526
150	84	665	89	693	86.5	679
180	84	817	94	857	89	837
210	87	972	97	1029	92	1000.5
240	90	1132	99	1207	94.5	1169.5
270	91	1297	102	1389	96.5	1343
300	93	1464	103	1574	98	1519
330	94	1632	104	1761	99	1696.5
360	94	1802	104	1949	99	1875.5

Table D.6 Statistical Analysis of ASTM C 1202 Tests of Group E and F Cores

	Group E & F Average		Standard Deviation
Time (minutes)	Current (mA)	Charge passed (coulombs)	Charge passed (coulombs)
1	63.8	3.3	0.5
30	71.5	121.3	8.8
60	75.3	254.3	17.3
90	80.5	395.3	28.1
120	84.5	544.8	40.2
150	88.0	700.8	54.5
180	90.8	863.0	69.4
210	93.3	1029.8	87.0
240	95.3	1200.5	105.4
270	96.8	1374.8	124.7
300	97.5	1550.8	145.5
330	98.0	1727.3	166.9
360	97.8	1904.3	188.5

Table D.7 Data Record and Statistical Analysis of ASTM C 1202 Tests of NI-0.40-0

	Sample 1		Sample 2		Average	Standard Deviation
Time (minutes)	Current (mA)	Charge passed (coulombs)	Current (mA)	Charge passed (coulombs)	Charge passed (coulombs)	Charge Passed (coulombs)
30	70	122	72	125	123.5	2.1
60	74	253	75	259	256	4.2
90	77	390	79	398	394	5.7
120	80	532	81	543	537.5	7.8
150	82	679	83	692	685.5	9.2
180	84	829	85	844	836.5	10.6
210	85	983	87	1000	991.5	12.0
240	87	1139	88	1159	1149	14.1
270	88	1297	89	1320	1308.5	16.3
300	89	1457	90	1483	1470	18.4
330	90	1619	91	1648	1633.5	20.5
360	90	1782	92	1814	1798.0	22.6

Table D.8 Data Record of ASTM C 1202 Tests of I-0.40-0

	Sample 1		**Sample 2**	
Time (minutes)	Current (mA)	Charge passed (coulombs)	Current (mA)	Charge passed (coulombs)
1	148	9	156	9
30	160	280	185	417
60	170	578	194	756
90	180	895	206	1118
120	191	1230	222	1504
150	201	1582	231	1911
180	208	1949	241	2339
210	215	2330	245	2777
240	220	2723	255	3228
270	226	3127	260	3693
300	233	3541	269	4171
330	235	3964	279	4664
360	241	4392	286	5173

Table D.9 Data Record of ASTM C 1202 Tests of I-0.40-0

	Sample 3		**Sample 4**	
Time (minutes)	Current (mA)	Charge passed (coulombs)	Current (mA)	Charge passed (coulombs)
1	133	8	157	9
30	143	248	170	305
60	151	514	180	620
90	159	794	190	960
120	166	1087	201	1313
150	172	1393	210	1683
180	181	1713	216	2073
210	187	2044	225	2471
240	188	2384	229	2880
270	196	2733	235	3300
300	198	3090	240	3731
330	203	3453	246	4170
360	204	3820	249	4616

Table D.10 Statistical Analysis of ASTM C 1202 Tests of I-0.40-0

	Average		**Standard Deviation**
Time (minutes)	Current (mA)	Charge passed (coulombs)	Charge passed (coulombs)
1	148.5	8.75	0.5
30	164.5	312.5	73.5
60	173.75	617	102.4
90	183.75	941.75	135.9
120	195	1283.5	174.1
150	203.5	1642.25	215.7
180	211.5	2018.5	260.7
210	218	2405.5	304.8
240	223	2803.75	350.5
270	229.25	3213.25	398.2
300	235	3633.25	448.1
330	240.75	4062.75	501.5
360	245	4500.25	559.9

APPENDIX E – DATA RECORD OF ASTM C 469 TESTS

Table E.1 Data record of ASTM C 469 test for cylinder 1 of G-1

Cast 1/7/03, Tested 3/18/04					
Load (lb)	Stress (psi)	Gauge Reading (in.)		Avg. Displacement (in.)	Strain (in/in)
		2nd Loading	3rd Loading		
1000	79.58	0.0000	0.0000	0.00000	0.00000
2000	159.15	0.0005	0.0005	0.00025	0.00005
3000	238.73	0.0005	0.0005	0.00025	0.00005
4000	318.31	0.0010	0.0010	0.00050	0.00009
5000	397.89	0.0010	0.0010	0.00050	0.00009
6000	477.46	0.0010	0.0010	0.00050	0.00009
7000	557.04	0.0010	0.0010	0.00050	0.00009
8000	636.62	0.0015	0.0015	0.00075	0.00014
9000	716.20	0.0015	0.0015	0.00075	0.00014
10000	795.77	0.0020	0.0020	0.00100	0.00019
11000	875.35	0.0020	0.0020	0.00100	0.00019
12000	954.93	0.0020	0.0020	0.00100	0.00019
13000	1034.51	0.0020	0.0020	0.00100	0.00019
14000	1114.08	0.0025	0.0025	0.00125	0.00024
15000	1193.66	0.0025	0.0025	0.00125	0.00024
16000	1273.24	0.0030	0.0030	0.00150	0.00028
17000	1352.82	0.0030	0.0030	0.00150	0.00028
18000	1432.39	0.0030	0.0030	0.00150	0.00028
19000	1511.97	0.0030	0.0030	0.00150	0.00028
20000	1591.55	0.0035	0.0035	0.00175	0.00033
21000	1671.13	0.0035	0.0035	0.00175	0.00033
22000	1750.70	0.0035	0.0035	0.00175	0.00033
23000	1830.28	0.0035	0.0040	0.00188	0.00035
24000	1909.86	0.0040	0.0040	0.00200	0.00038
25000	1989.44	0.0040	0.0040	0.00200	0.00038
26000	2069.01	0.0040	0.0040	0.00200	0.00038
27000	2148.59	0.0045	0.0045	0.00225	0.00042
28000	2228.17	0.0045	0.0045	0.00225	0.00042
29000	2307.75	0.0045	0.0045	0.00225	0.00042
30000	2387.32	0.0045	0.0050	0.00238	0.00045
31000	2466.90	0.0050	0.0050	0.00250	0.00047
32000	2546.48	0.0050	0.0050	0.00250	0.00047

Table E.1 (cont.)

Load (lb)	Stress (psi)	Gauge Reading (in.)		Avg. Displacement (in.)	Strain (in/in)
		2nd Loading	3rd Loading		
33000	2626.06	0.0055	0.0055	0.00275	0.00052
34000	2705.63	0.0055	0.0055	0.00275	0.00052

Table E.2 Data record of ASTM C 469 test of cylinder 2 of G-1

Cast 1/7/03, Tested 3/18/04					
Load (lb)	Stress (psi)	Gauge Reading (in.)		Avg. Displacement (in.)	Strain (in/in)
		2nd Loading	3rd Loading		
1000	79.58	0.0000	0.0000	0.00000	0.00000
2000	159.15	0.0005	0.0005	0.00025	0.00005
3000	238.73	0.0005	0.0005	0.00025	0.00005
4000	318.31	0.0005	0.0005	0.00025	0.00005
5000	397.89	0.0010	0.0010	0.00050	0.00009
6000	477.46	0.0010	0.0010	0.00050	0.00009
7000	557.04	0.0010	0.0010	0.00050	0.00009
8000	636.62	0.0015	0.0015	0.00075	0.00014
9000	716.20	0.0015	0.0015	0.00075	0.00014
10000	795.77	0.0020	0.0020	0.00100	0.00019
11000	875.35	0.0020	0.0020	0.00100	0.00019
12000	954.93	0.0020	0.0020	0.00100	0.00019
13000	1034.51	0.0020	0.0020	0.00100	0.00019
14000	1114.08	0.0025	0.0025	0.00125	0.00024
15000	1193.66	0.0025	0.0025	0.00125	0.00024
16000	1273.24	0.0025	0.0030	0.00138	0.00026
17000	1352.82	0.0030	0.0030	0.00150	0.00028
18000	1432.39	0.0030	0.0030	0.00150	0.00028
19000	1511.97	0.0030	0.0030	0.00150	0.00028
20000	1591.55	0.0035	0.0035	0.00175	0.00033
21000	1671.13	0.0035	0.0035	0.00175	0.00033
22000	1750.70	0.0035	0.0035	0.00175	0.00033
23000	1830.28	0.0035	0.0035	0.00175	0.00033
24000	1909.86	0.0040	0.0040	0.00200	0.00038
25000	1989.44	0.0040	0.0040	0.00200	0.00038
26000	2069.01	0.0040	0.0040	0.00200	0.00038

Table E.2 (cont.)

Load (lb)	Stress (psi)	Gauge Reading (in.) 2nd Loading	Gauge Reading (in.) 3rd Loading	Avg. Displacement (in.)	Strain (in/in)
27000	2148.59	0.0045	0.0045	0.00225	0.00042
28000	2228.17	0.0045	0.0045	0.00225	0.00042
29000	2307.75	0.0045	0.0045	0.00225	0.00042
32000	2546.48	0.0050	0.0050	0.00250	0.00047
33000	2626.06	0.0055	0.0055	0.00275	0.00052
34000	2705.63	0.0055	0.0055	0.00275	0.00052

Table E.3 Data record of ASTM C 469 test of cylinder 3 of G-2

Cast 1/7/03, Tested 3/18/04					
Load (lb)	Stress (psi)	Gauge Reading (in.) 2nd Loading	Gauge Reading (in.) 3rd Loading	Avg. Displacement (in.)	Strain (in/in)
1000	79.58	0.0000	0.0000	0.00000	0.00000
2000	159.15	0.0000	0.0000	0.00000	0.00000
3000	238.73	0.0000	0.0005	0.00013	0.00002
4000	318.31	0.0005	0.0005	0.00025	0.00005
5000	397.89	0.0005	0.0005	0.00025	0.00005
6000	477.46	0.0010	0.0010	0.00050	0.00009
7000	557.04	0.0010	0.0010	0.00050	0.00009
8000	636.62	0.0010	0.0010	0.00050	0.00009
9000	716.20	0.0015	0.0015	0.00075	0.00014
10000	795.77	0.0015	0.0015	0.00075	0.00014
11000	875.35	0.0015	0.0020	0.00088	0.00017
12000	954.93	0.0020	0.0020	0.00100	0.00019
13000	1034.51	0.0020	0.0020	0.00100	0.00019
14000	1114.08	0.0020	0.0020	0.00100	0.00019
15000	1193.66	0.0025	0.0025	0.00125	0.00024
16000	1273.24	0.0025	0.0025	0.00125	0.00024
17000	1352.82	0.0025	0.0025	0.00125	0.00024
18000	1432.39	0.0030	0.0030	0.00150	0.00028
19000	1511.97	0.0030	0.0030	0.00150	0.00028
20000	1591.55	0.0030	0.0030	0.00150	0.00028
21000	1671.13	0.0035	0.0035	0.00175	0.00033
22000	1750.70	0.0035	0.0035	0.00175	0.00033
23000	1830.28	0.0035	0.0035	0.00175	0.00033

Table E.3 (cont.)

Load (lb)	Stress (psi)	Gauge Reading (in.)		Avg. Displacement (in.)	Strain (in/in)
		2nd Loading	3rd Loading		
24000	1909.86	0.0035	0.0035	0.00175	0.00033
25000	1989.44	0.0040	0.0040	0.00200	0.00038
26000	2069.01	0.0040	0.0040	0.00200	0.00038
27000	2148.59	0.0040	0.0040	0.00200	0.00038
32000	2546.48	0.0050	0.0050	0.00250	0.00047
33000	2626.06	0.0050	0.0050	0.00250	0.00047
34000	2705.63	0.0055	0.0055	0.00275	0.00052

Table E.4 Data record of ASTM C 469 test of cylinder 1 of G-2

Cast 1/20/03, Tested 3/18/04					
Load (lb)	Stress (psi)	Gauge Reading (in.)		Avg. Displacement (in.)	Strain (in/in)
		2nd Loading	3rd Loading		
1000	79.58	0.0000	0.0000	0.00000	0.00000
2000	159.15	0.0000	0.0000	0.00000	0.00000
3000	238.73	0.0000	0.0000	0.00000	0.00000
4000	318.31	0.0000	0.0000	0.00000	0.00000
5000	397.89	0.0005	0.0005	0.00025	0.00005
6000	477.46	0.0005	0.0005	0.00025	0.00005
7000	557.04	0.0005	0.0005	0.00025	0.00005
8000	636.62	0.0010	0.0010	0.00050	0.00009
9000	716.20	0.0010	0.0010	0.00050	0.00009
10000	795.77	0.0010	0.0010	0.00050	0.00009
11000	875.35	0.0015	0.0015	0.00075	0.00014
12000	954.93	0.0015	0.0015	0.00075	0.00014
13000	1034.51	0.0015	0.0015	0.00075	0.00014
14000	1114.08	0.0020	0.0020	0.00100	0.00019
15000	1193.66	0.0020	0.0020	0.00100	0.00019
16000	1273.24	0.0020	0.0020	0.00100	0.00019
17000	1352.82	0.0020	0.0020	0.00100	0.00019
18000	1432.39	0.0025	0.0025	0.00125	0.00024
19000	1511.97	0.0025	0.0025	0.00125	0.00024
20000	1591.55	0.0025	0.0025	0.00125	0.00024
21000	1671.13	0.0030	0.0030	0.00150	0.00028
22000	1750.70	0.0030	0.0030	0.00150	0.00028

Table E.4 (cont.)

Load (lb)	Stress (psi)	Gauge Reading (in.)		Avg. Displacement (in.)	Strain (in/in)
		2nd Loading	3rd Loading		
23000	1830.28	0.0030	0.0030	0.00150	0.00028
24000	1909.86	0.0035	0.0035	0.00175	0.00033
25000	1989.44	0.0035	0.0035	0.00175	0.00033
26000	2069.01	0.0035	0.0035	0.00175	0.00033
27000	2148.59	0.0035	0.0035	0.00175	0.00033
28000	2228.17	0.0040	0.0040	0.00200	0.00038
29000	2307.75	0.0040	0.0040	0.00200	0.00038
30000	2387.32	0.0045	0.0045	0.00225	0.00042
31000	2466.90	0.0045	0.0045	0.00225	0.00042
32000	2546.48	0.0045	0.0045	0.00225	0.00042
33000	2626.06	0.0045	0.0045	0.00225	0.00042
34000	2705.63	0.0050	0.0050	0.00250	0.00047
35000	2785.21	0.0050	0.0050	0.00250	0.00047
36000	2864.79	0.0050	0.0050	0.00250	0.00047
37000	2944.37	0.0055	0.0055	0.00275	0.00052
38000	3023.94	0.0055	0.0055	0.00275	0.00052

Table E.5 Data record of ASTM C 469 test of cylinder 2 of G-2

Cast 1/20/03, Tested 3/18/04					
Load (lb)	Stress (psi)	Gauge Reading (in.)		Avg. Displacement (in.)	Strain (in/in)
		2nd Loading	3rd Loading		
1000	79.58	0.0000	0.0000	0.00000	0.00000
2000	159.15	0.0000	0.0000	0.00000	0.00000
3000	238.73	0.0000	0.0000	0.00000	0.00000
4000	318.31	0.0005	0.0005	0.00025	0.00005
5000	397.89	0.0005	0.0005	0.00025	0.00005
6000	477.46	0.0005	0.0005	0.00025	0.00005
7000	557.04	0.0010	0.0010	0.00050	0.00009
8000	636.62	0.0010	0.0010	0.00050	0.00009
9000	716.20	0.0010	0.0010	0.00050	0.00009
10000	795.77	0.0010	0.0015	0.00063	0.00012
11000	875.35	0.0015	0.0015	0.00075	0.00014
12000	954.93	0.0015	0.0015	0.00075	0.00014
13000	1034.51	0.0020	0.0020	0.00100	0.00019

Table E.5 (cont.)

Load (lb)	Stress (psi)	Gauge Reading (in.) 2nd Loading	Gauge Reading (in.) 3rd Loading	Avg. Displacement (in.)	Strain (in/in)
14000	1114.08	0.0020	0.0020	0.00100	0.00019
15000	1193.66	0.0020	0.0020	0.00100	0.00019
16000	1273.24	0.0020	0.0020	0.00100	0.00019
17000	1352.82	0.0020	0.0020	0.00100	0.00019
18000	1432.39	0.0025	0.0025	0.00125	0.00024
19000	1511.97	0.0025	0.0025	0.00125	0.00024
20000	1591.55	0.0030	0.0030	0.00150	0.00028
21000	1671.13	0.0030	0.0030	0.00150	0.00028
22000	1750.70	0.0030	0.0030	0.00150	0.00028
23000	1830.28	0.0030	0.0030	0.00150	0.00028
24000	1909.86	0.0035	0.0035	0.00175	0.00033
25000	1989.44	0.0035	0.0035	0.00175	0.00033
26000	2069.01	0.0035	0.0035	0.00175	0.00033
27000	2148.59	0.0035	0.0035	0.00175	0.00033
28000	2228.17	0.0040	0.0040	0.00200	0.00038
29000	2307.75	0.0040	0.0040	0.00200	0.00038
30000	2387.32	0.0040	0.0040	0.00200	0.00038
31000	2466.90	0.0045	0.0045	0.00225	0.00042
32000	2546.48	0.0045	0.0045	0.00225	0.00042
33000	2626.06	0.0045	0.0045	0.00225	0.00042
34000	2705.63	0.0045	0.0045	0.00225	0.00042
35000	2785.21	0.0050	0.0050	0.00250	0.00047
36000	2864.79	0.0050	0.0050	0.00250	0.00047
37000	2944.37	0.0055	0.0055	0.00275	0.00052
38000	3023.94	0.0055	0.0055	0.00275	0.00052

Table E.6 Data record of ASTM C 469 test of cylinder 3 of G-2

Cast 1/20/03, Tested 3/18/04					
		Gauge Reading (in.)			
Load (lb)	Stress (psi)	2nd Loading	3rd Loading	Avg. Displacement (in.)	Strain (in/in)
1000	79.58	0.0000	0.0000	0.00000	0.00000
2000	159.15	0.0005	0.0005	0.00025	0.00005
3000	238.73	0.0005	0.0005	0.00025	0.00005
4000	318.31	0.0010	0.0010	0.00050	0.00009
5000	397.89	0.0010	0.0010	0.00050	0.00009
6000	477.46	0.0010	0.0010	0.00050	0.00009
7000	557.04	0.0010	0.0010	0.00050	0.00009
8000	636.62	0.0010	0.0010	0.00050	0.00009
9000	716.20	0.0015	0.0015	0.00075	0.00014
10000	795.77	0.0015	0.0015	0.00075	0.00014
11000	875.35	0.0020	0.0020	0.00100	0.00019
12000	954.93	0.0020	0.0020	0.00100	0.00019
13000	1034.51	0.0020	0.0020	0.00100	0.00019
14000	1114.08	0.0020	0.0020	0.00100	0.00019
15000	1193.66	0.0020	0.0020	0.00100	0.00019
16000	1273.24	0.0025	0.0025	0.00125	0.00024
17000	1352.82	0.0025	0.0025	0.00125	0.00024
18000	1432.39	0.0030	0.0030	0.00150	0.00028
19000	1511.97	0.0030	0.0030	0.00150	0.00028
20000	1591.55	0.0030	0.0030	0.00150	0.00028
21000	1671.13	0.0030	0.0030	0.00150	0.00028
22000	1750.70	0.0035	0.0035	0.00175	0.00033
23000	1830.28	0.0035	0.0035	0.00175	0.00033
24000	1909.86	0.0035	0.0035	0.00175	0.00033
25000	1989.44	0.0035	0.0035	0.00175	0.00033
26000	2069.01	0.0040	0.0040	0.00200	0.00038
27000	2148.59	0.0040	0.0040	0.00200	0.00038
28000	2228.17	0.0040	0.0040	0.00200	0.00038
29000	2307.75	0.0045	0.0045	0.00225	0.00042
30000	2387.32	0.0045	0.0045	0.00225	0.00042
31000	2466.90	0.0045	0.0045	0.00225	0.00042
32000	2546.48	0.0045	0.0045	0.00225	0.00042
33000	2626.06	0.0050	0.0050	0.00250	0.00047
34000	2705.63	0.0050	0.0050	0.00250	0.00047

Table E.6 (cont.)

Load (lb)	Stress (psi)	Gauge Reading (in.)		Avg. Displacement (in.)	Strain (in/in)
		2nd Loading	3rd Loading		
35000	2785.21	0.0050	0.0050	0.00250	0.00047
36000	2864.79	0.0055	0.0055	0.00275	0.00052
37000	2944.37	0.0055	0.0055	0.00275	0.00052
38000	3023.94	0.0055	0.0055	0.00275	0.00052

APPENDIX F – FRESH AND HARDENED PROPERTIES OF IPANEX AND NON-IPANEX BRIDGE DECK CONCRETE FROM BRIDGE OVER CHIKASKIA RIVER ON I-35, IN KAY COUNTY, OKLAHOMA

Table F.1 Fresh and Hardened Properties of Span 1 of Northbound Bridge

Northbound Bridge (with IPANEX)	
Span	1
Date Cast	1/7/2003
Time	10:48
Air Temp. (°F)	37
Fresh Properties	
Concrete Temp.(°F)	64
Slump (in.)	6.5
Air Content (%)	5.5
Unit Weight (pcf)	N/A
Hardened Properties	
Average 7 Day Strength (psi)	
4789	
Average 28 Day Strength (psi)	
5588	

Table F.2 Fresh and Hardened Properties of Span 2 of Northbound Bridge

Northbound Bridge (with IPANEX)	
Span	2
Date Cast	1/8/2003
Time	9:15
Air Temp. (°F)	40
Fresh Properties	
Concrete Temp.(°F)	69
Slump (in.)	7.25
Air Content (%)	8.5
Unit Weight (pcf)	N/A
Hardened Properties	
Average 7 Day Strength (psi)	
3410	
Average 28 Day Strength (psi)	
4485	

Table F.3 Fresh and Hardened Properties of Span 2 of Northbound Bridge

Northbound Bridge (with IPANEX)	
Span	2
Date Cast	1/8/2003
Time	10:30
Air Temp. (°F)	50
Fresh Properties	
Concrete Temp.(°F)	71
Slump (in.)	5.75
Air Content (%)	7.9
Unit Weight (pcf)	N/A
Hardened Properties	
Average 7 Day Strength (psi)	
3287	
Average 28 Day Strength (psi)	
4312	

Table F.4 Fresh and Hardened Properties of Span 3 of Northbound Bridge

Northbound Bridge (with IPANEX)	
Span	3
Date Cast	1/20/2003
Time	9:15
Air Temp. (°F)	45
Fresh Properties	
Concrete Temp.(°F)	65
Slump (in.)	3
Air Content (%)	5
Unit Weight (pcf)	147.9
Hardened Properties	
Average 7 Day Strength (psi)	
4655	
Average 28 Day Strength (psi)	
5525	

Table F.5 Fresh and Hardened Properties of Span 3 of Northbound Bridge

Northbound Bridge (with IPANEX)	
Span	3
Date Cast	1/20/2003
Time	10:15
Air Temp. (°F)	50
Fresh Properties	
Concrete Temp.(°F)	65
Slump (in.)	5.75
Air Content (%)	6
Unit Weight (pcf)	145.9
Hardened Properties	
Average 7 Day Strength (psi)	
3889	
Average 28 Day Strength (psi)	
4994	

Table F.6 Fresh and Hardened Properties of Span 4 of Northbound Bridge

Northbound Bridge (with IPANEX)	
Span	4
Date Cast	1/20/2003
Time	11:40
Air Temp. (°F)	55
Fresh Properties	
Concrete Temp.(°F)	65
Slump (in.)	6
Air Content (%)	7.8
Unit Weight (pcf)	124.6
Hardened Properties	
Average 7 Day Strength (psi)	
4107	
Average 28 Day Strength (psi)	
4709	

Table F.7 Fresh and Hardened Properties of Span 4 of Northbound Bridge

Northbound Bridge (with IPANEX)	
Span	4
Date Cast	1/20/2003
Time	12:40
Air Temp. (°F)	58
Fresh Properties	
Concrete Temp.(°F)	68
Slump (in.)	5
Air Content (%)	6
Unit Weight (pcf)	141.5
Hardened Properties	
Average 7 Day Strength (psi)	
3339	
Average 28 Day Strength (psi)	
5683	

Table F.8 Fresh and Hardened Properties of Span 5 of Northbound Bridge

Northbound Bridge (with IPANEX)	
Span	5
Date Cast	1/28/2003
Time	9:20
Air Temp. (°F)	45
Fresh Properties	
Concrete Temp.(°F)	55
Slump (in.)	2.75
Air Content (%)	5.6
Unit Weight (pcf)	148.3
Hardened Properties	
Average 7 Day Strength (psi)	
3978	
Average 28 Day Strength (psi)	
5133	

Table F.9 Fresh and Hardened Properties of Span 5 of Northbound Bridge

Northbound Bridge (with IPANEX)	
Span	5
Date Cast	1/28/2003
Time	10:30
Air Temp. (°F)	45
Fresh Properties	
Concrete Temp.(°F)	55
Slump (in.)	5
Air Content (%)	7.5
Unit Weight (pcf)	145.1
Hardened Properties	
Average 7 Day Strength (psi)	
3278	
Average 28 Day Strength (psi)	
4365	

Table F.10 Fresh and Hardened Properties of Span 1 of Southbound Bridge

Southbound Bridge (without IPANEX)	
Span	1
Date Cast	3/6/2002
Time	9:40
Air Temp. (°F)	50
Fresh Properties	
Concrete Temp.(°F)	56
Slump (in.)	7
Air Content (%)	6.1
Unit Weight (pcf)	N/A
Hardened Properties	
Average 7 Day Strength (psi)	
4163	
Average 28 Day Strength (psi)	
5504	

Table F.11 Fresh and Hardened Properties of Span 1 of Southbound Bridge

Southbound Bridge (without IPANEX)	
Span	1
Date Cast	3/6/2002
Time	10:40
Air Temp. (°F)	55
Fresh Properties	
Concrete Temp.(°F)	56
Slump (in.)	7.5
Air Content (%)	6.9
Unit Weight (pcf)	146.3
Hardened Properties	
Average 7 Day Strength (psi)	
3767	
Average 28 Day Strength (psi)	
5427	

Table F.12 Fresh and Hardened Properties of Span 2 of Southbound Bridge

Southbound Bridge (without IPANEX)	
Span	2
Date Cast	3/8/2002
Time	10:00
Air Temp. (°F)	61
Fresh Properties	
Concrete Temp.(°F)	65
Slump (in.)	9
Air Content (%)	6.5
Unit Weight (pcf)	146.3
Hardened Properties	
Average 7 Day Strength (psi)	
3238	
Average 28 Day Strength (psi)	
4966	

Table F.13 Fresh and Hardened Properties of Span 1 & 2 Enclosure of Southbound Bridge

Southbound Bridge (without IPANEX)	
Span	1 & 2 Enclosure
Date Cast	3/11/2002
Time	9:30
Air Temp. (°F)	45
Fresh Properties	
Concrete Temp.(°F)	67
Slump (in.)	6.5
Air Content (%)	5
Unit Weight (pcf)	151.1
Hardened Properties	
Average 7 Day Strength (psi)	
4676	
Average 28 Day Strength (psi)	
5520	

Table F.14 Fresh and Hardened Properties of Span 3 of Southbound Bridge

Southbound Bridge (without IPANEX)	
Span	3
Date Cast	3/11/2002
Time	11:15
Air Temp. (°F)	53
Fresh Properties	
Concrete Temp.(°F)	57
Slump (in.)	8
Air Content (%)	5.7
Unit Weight (pcf)	146.3
Hardened Properties	
Average 7 Day Strength (psi)	
4403	
Average 28 Day Strength (psi)	
5288	

Table F.15 Fresh and Hardened Properties of Span 4 of Southbound Bridge

Southbound Bridge (without IPANEX)	
Span	4
Date Cast	3/12/2002
Time	9:15
Air Temp. (°F)	40
Fresh Properties	
Concrete Temp.(°F)	54
Slump (in.)	6.75
Air Content (%)	6.4
Unit Weight (pcf)	N/A
Hardened Properties	
Average 7 Day Strength (psi)	
3571	
Average 28 Day Strength (psi)	
5118	

Table F.16 Fresh and Hardened Properties of Span 4 of Southbound Bridge

Southbound Bridge (without IPANEX)	
Span	4
Date Cast	3/12/2002
Time	10:05
Air Temp. (°F)	45
Fresh Properties	
Concrete Temp.(°F)	55
Slump (in.)	5.5
Air Content (%)	6.4
Unit Weight (pcf)	N/A
Hardened Properties	
Average 7 Day Strength (psi)	
3111	
Average 28 Day Strength (psi)	
4708	

Table F.17 Fresh and Hardened Properties of Span 5 of Southbound Bridge

Southbound Bridge (without IPANEX)	
Span	5
Date Cast	3/12/2002
Time	12:05
Air Temp. (°F)	56
Fresh Properties	
Concrete Temp.(°F)	64
Slump (in.)	5.5
Air Content (%)	5
Unit Weight (pcf)	150.7
Hardened Properties	
Average 7 Day Strength (psi)	
3502	
Average 28 Day Strength (psi)	
4861	

Table F.18 Fresh and Hardened Properties of Span 5 of Southbound Bridge

Southbound Bridge (without IPANEX)	
Span	5
Date Cast	3/12/2002
Time	1:15
Air Temp. (°F)	68
Fresh Properties	
Concrete Temp.(°F)	56
Slump (in.)	4.75
Air Content (%)	4.5
Unit Weight (pcf)	N/A
Hardened Properties	
Average 7 Day Strength (psi)	
4084	
Average 28 Day Strength (psi)	
5525	

Table F.19 Fresh and Hardened Properties of Span 2 & 3 Enclosure of Southbound Bridge

Southbound Bridge (without IPANEX)	
Span	2 & 3 Enclosure
Date Cast	3/14/2002
Time	9:00
Air Temp. (°F)	58
Fresh Properties	
Concrete Temp.(°F)	65
Slump (in.)	7
Air Content (%)	7
Unit Weight (pcf)	N/A
Hardened Properties	
Average 7 Day Strength (psi)	
3645	
Average 28 Day Strength (psi)	
4942	

Table F.20 Fresh and Hardened Properties of Span 4 & 5 Enclosure of Southbound Bridge

Southbound Bridge (without IPANEX)	
Span	4 & 5 Enclosure
Date Cast	3/14/2002
Time	10:45
Air Temp. (°F)	65
Fresh Properties	
Concrete Temp.(°F)	68
Slump (in.)	4.5
Air Content (%)	5.2
Unit Weight (pcf)	N/A
Hardened Properties	
Average 7 Day Strength (psi)	
4240	
Average 28 Day Strength (psi)	
5226	

VITA

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