



Field Testing of Rapid Electrokinetic Nanoparticle Treatment for Corrosion Control of Steel in Concrete

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ABBREVIATIONS AND ACRONYMS

A	ampere
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BCTS	Beach Corrosion Test Site
ca	calcium
C-S-H	calcium silicate hydrate
d	diameter
ECE	electrochemical chloride extraction
EDS	Energy Dispersive X-Ray Spectroscopic
EN	electrokinetic nanoparticle
et al.	and others
ft	foot
in	inch
KIP	Kennedy Internship Program
L	liter, length
m	meter
mA	milliampere
min	minute
mL	milliliter
mm	millimeter
mpy	mils per year
NaCl	sodium chloride
nm	nanometer
PI	principle investigator
psi	pound per square inch
SEM	scanning electron microscopic
SF	silica fume
S.H.E.	standard hydrogen electrode
TM	Technical Manual
V	volt
wt.%	weight percent

π	pi
σ	sigma
P	load in pounds

ABSTRACT

This work field tested the use of electrokinetics for delivery of concrete sealing nanoparticles concurrent with the extraction of chlorides. Several cylinders of concrete were batched and placed in immersion at the Kennedy Space Center Beach Corrosion Test Site. The specimens were batched with steel reinforcement and a 4.5 wt.% (weight percent) content of sodium chloride. Upon arrival at Kennedy Space Center, the specimens were placed in the saltwater immersion pool at the Beach Corrosion Test Site. Following 30 days of saltwater exposure, the specimens were subjected to rapid chloride extraction concurrent with electrokinetic nanoparticle treatment. The treatments were operated at up to eight times the typical current density in order to complete the treatment in 7 days. The findings indicated that the short-term corrosion resistance of the concrete specimens was significantly enhanced as was the strength of the concrete.

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FIELD TESTING OF RAPID ELECTROKINETIC NANOPARTICLE TREATMENT FOR CORROSION CONTROL OF STEEL IN CONCRETE

1 INTRODUCTION

In 2001, the U.S. Federal Highway Administration, in concert with CC Technologies Laboratories Inc., finalized a landmark study on the direct costs of corrosion in nearly every major U.S. industrial sector (Koch et al., 2002). Corrosion in bridge structures is a global problem. The study found that the annual direct cost of highway bridge repairs (largely related to reinforcement corrosion) was \$8.3 billion in the U.S. alone. The proposed electrokinetic approach is intended to provide a radical increase in the durability of concrete repairs by removing aggressive chemical species and sealing the region with a close chemical relative of the original cement binder material in ordinary portland cement. Figure 1 contains a schematic representation of a treatment applied to reinforced concrete. Such a treatment may provide a sound foundation for application of traditional repair materials that would otherwise be undermined by continued reinforcement corrosion. An adaptation of this technology could become a cost-effective repair method for bridges, basements, and other structures. Unlike a typical coating, pozzolanic nanoparticles penetrate almost as deeply as desired with a minimal electric field as small as 1 volt/inch and a current draw of less than 0.1 ampere per square foot. The electric field provides a targeted treatment that eventually could be applied in the field and go preferentially to where the porosity, cracking and steel reinforcement is most needful of remedy. Conventional coatings and topical repairs do not provide this efficiency since they must be applied evenly over the entire surface to ensure coverage.

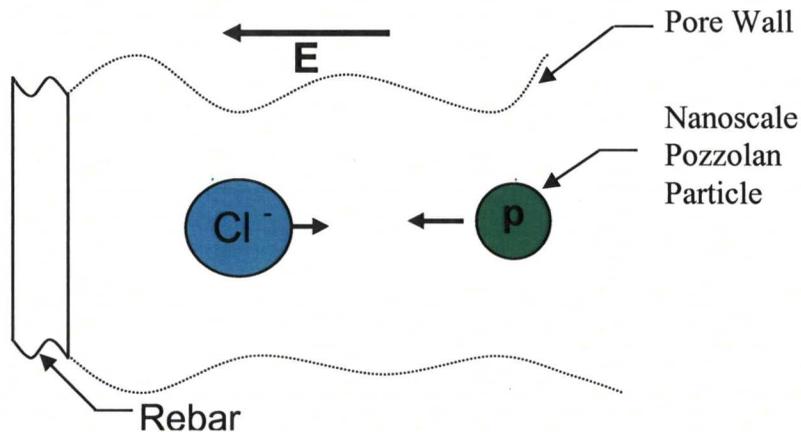


Figure 1. Reactive Electrokinetic Treatment in Cement Matrix

2 BACKGROUND

In concrete, the elevated pH causes steel reinforcement to develop a passive oxide film that effectively protects it against corrosion. The reduction of this pH or the introduction of aggressive chemical species can cause this passive film to be disrupted (Reinhardt, 1992, Samaha, 1992, Luping and Nilsson, 1993, Pigeon et al., 1993, Johansen et al., 1995, and Huang et al., 2005). Both of these possibilities may arise from a failure in the concrete cover material. If the concrete cover is too porous or contains cracks, external chemical species can migrate to the reinforcement relatively quickly. If carbon dioxide is absorbed into the pore fluid, it will reduce the pH of the environment. The lowered pH does not support the passive film. This condition allows the iron in the steel to corrode and form oxides. These oxides are the corrosion product or rust that is observed on the surface of corroding steel. Growth of this oxide layer causes the surrounding concrete to experience tensile stresses. The stresses that can be developed as a result of corrosion product buildup can be in the vicinity of 10,000 pounds per square inch (psi). In contrast, concrete tends to suffer tensile cracking as these stresses approach 300 to 1000 psi. Resultant cracking tends to provide passage for aggressive species. Due to the application of de-icing salts, exposure to marine environments, or even the usage of coastal sand, chloride ions become available. The chloride ion causes rapid corrosion of steel bars in concrete (Jung, 2003). A major issue here is that the chloride ion is not consumed in the corrosion process (Jones, p. 388, 1992). It acts as a reaction catalyst that is continuously recycled. For this reason, many concrete repairs continue to suffer from corrosion because the repair failed to reduce the chloride content of the structure. With the chlorides eliminated, or at least reduced in concentration as compared to the pH, the life of a properly repaired structure is significantly extended (Johnson, 1997).

Hardened cement paste, the binder that holds concrete together, is a porous material. Durability problems commonly occur when this porosity is too high (Mindess et al., p. 477, 1996). There are some remedies that can be applied to reduce permeability at the surface of a structure. Water seepage through cementitious materials is addressed using polymer coatings, reactive organic and inorganic grouts, and application of pulsed electric current (Taylor, p. 361, 1997, Xypex, 1983; Vandex, 1983; and Mindess et al., p. 511, 1996). Electric current is occasionally used to induce electro-osmosis in the direction opposing flow (Finney, 1998). Typically, electro-osmosis is used concurrent with standard techniques such as chiseling out faulty joints and applying grouts and sealers at these locations and throughout the structure (Hock, 1998).

When used either as partial replacements or additions to portland cement, silica fume (SF) and fly ash are well recognized for reducing the permeability of concrete (Baker, 1980). These materials are called pozzolans. They form chemically close variants of calcium silicate hydrate (C-S-H) when they come into contact with a source of calcium such as calcium hydroxide (which can make up over 25% of the binder phase in a given concrete). It has also been found that these modifiers can also draw calcium from C-S-H. Using nuclear magnetic resonance, Lagerblad et al. (2003) found that liberal addition of SF decreased the Ca/Si ratio of C-S-H. For example, a 5% SF addition to a mix achieved a CaO/SiO₂ ratio of 1.8 and a 40% SF addition provided a ratio of 0.9. Bhanja et al. (2004) studied the influence of silica fume on the tensile strength of concrete, reporting a typical 20% improvement when SF replacement levels ranged from 5% to 25%.

Colloidal silica and sodium silicate have also been used to improve the strength of cementitious materials. Some researchers have investigated the addition of these agents as partial water replacements. Chandra et al. (1997) found that, because of the finer size of the colloidal silica, this material exhibits faster reactivity than SF. Nelson et al. (1977) investigated the pozzolanic reactivity of colloidal silica and quaternary ammonium silicate in portland cement pastes. This work showed higher strengths than plain concrete for 150 days after the batch. The study did not supply strength data after 150 days. Campillo et al. (2003) studied the influence of nanoscale colloidal silica on cement properties. Improved compression strength was observed. The reason cited for strength improvement is that reaction products are formed within the pores, reducing porosity.

Another means of reducing porosity or at least obstructing pores is by using an electric field to transport passive or reactive species into a water-saturated, porous medium. A paper manufacturing process patented in Europe involves the electrokinetic transport of reactive pore-blocking agents that chemically react with some elements of the flow path (Ortlepp, 1992). This process influences the pore structure and the chemistry of the paper. Even earlier mention of this concept in England involved unspecified reactive agents being pumped into the soil side of a leaking basement followed by application of an electric field (Gratwick, p. 163, 1974). A similar concept directed toward crack repair was found to achieve some success in reducing the permeability of damaged concrete (Otsuki et al., 2001 and Ryu, et al., 2002). Other work examined mixtures of silica fume and calcium hydroxide as a mechanically applied crack repair agent (Kasselouri et al., 2001). The transport and strengthening characteristics of active or passive blocking agents in concrete are not well understood.

Active blocking agents for electrokinetic permeability reduction in hardened cement paste were first studied in 2002 (Cardenas, 2002 and Cardenas and Struble, 2006). This work examined the feasibility of transporting nano-scale pozzolans into hardened cement paste pores using an electric field and demonstrating active pore blocking and permeability reduction. The pozzolans, silicate and aluminate solutions and colloids, were found to reduce permeability of highly porous cement paste by a factor of 1000 in some cases. In 2004, the work focused on mitigating corrosion by transporting nanoparticles (electrokinetic nanoparticle [EN] treatment) into concrete specimens using a weak electric field for 10 days (Cardenas and Goli, 2006). The charge of the particles allowed a circuit polarity that also extracted chloride ions. The nanoparticles apparently reacted within the pores of the concrete and reduced the permeability. Concrete specimens exposed to saltwater were treated using both electrochemical chloride extraction (ECE) and EN methods. The corrosion potentials of the steel reinforcement were monitored. The findings of this treatment indicated that when compared to ECE, the EN-treated regions of these specimens slowed the return migration of chloride ions by a factor of 2-3. A region of 10 to 15 millimeter (mm) of treatment penetration was observed in the EN-treated specimens, following a 10-day treatment with 20 nanometer (nm) positively charged silica particles. Indirect tensile splitting tests of these cylindrical specimens revealed an increase in strength of the EN-treated regions of ~50% as compared to the chloride extracted specimens and the control specimens. Scanning electron microscopic (SEM) analysis indicated apparent densification of the treated concrete region. In 2004, other work examined nanoparticle treatments in fresh concrete (immediately after batching) that demonstrated increases in bending strength in 4-inch-thick bending specimens loaded in third point bending (Zhao and Cardenas, 2006).

In 2006, a new approach examined the use of 24-nm, positively charged silica particles for EN treatments in which the steel reinforcement was used as the cathode (Cardenas and Kupwade-Patil, 2007). In this treatment the positively charged particles were drawn directly to the reinforcement while chloride ions were being driven away. The intention was to develop a chemical and structural corrosion barrier around the reinforcement. Initially, the treatment drew sodium, potassium, and calcium ions to the bar surface, increasing the local alkalinity while driving away chlorides. Either of these ion movements by themselves could bring corrosion under control. Combining them tends to enhance the result. Later, as the nanoparticles arrived, they were expected to react with available calcium to form a C-S-H barrier around the realkalized region. Additional particle loading was provided to fortify this physical barrier as more calcium becomes available further back from the reinforcement. The intention was that the physical barrier would “keep” the alkali metals close to the reinforcement while slowing/preventing the return of chlorides or other aggressive species. See Figure 2.

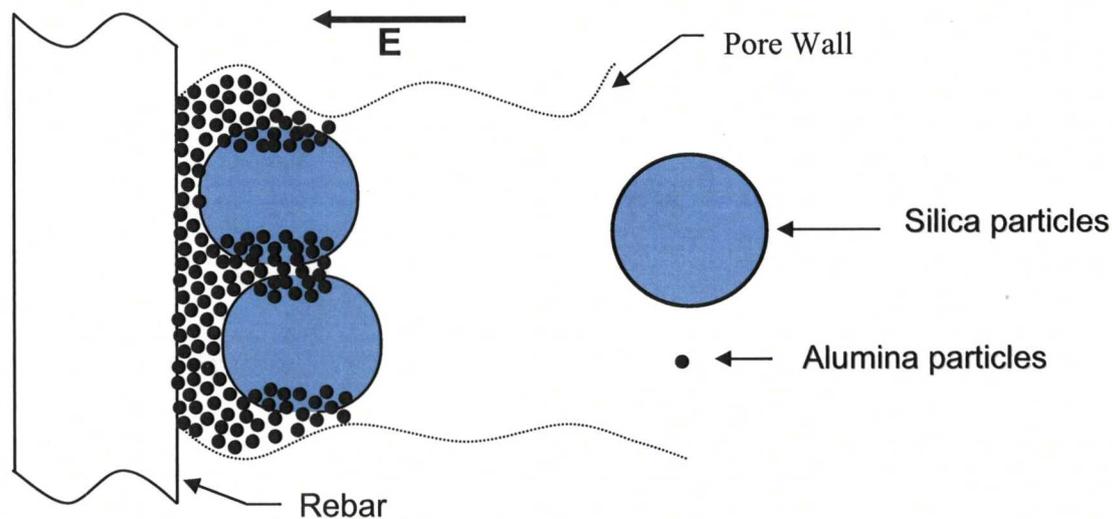


Figure 2. Predicted Formation of Particles in Cement Matrix After Treatment

The 14-day-old, cylindrical, concrete specimens with 1018 steel reinforcement were exposed to salt water solution for a period of 14 days (Cardenas and Kupwadi-Patil, 2007). After the initiation of corrosion was signaled (by a negative shift in corrosion potential), the specimens were subjected to ECE for a period of 14 days. After 14 days of ECE, some of the specimens were subjected to EN treatment. The concurrent EN and ECE treatments continued for 14 more days. This ensured an equal time period of chloride exposure for comparable test cases. Following 30 days of chloride reexposure the specimens were subjected to indirect tension testing in accordance with ASTM C496-96, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. The steel reinforcement was examined directly after tensile testing. A small amount of corrosion products was observed on the EN-treated specimen reinforcement bars (< 2 % of the surface areas). This observation was consistent with the fact that all cases were exposed to saltwater until corrosion activity was detected. The treated

specimens showed little damage while the untreated controls were severely corroded. The controls exhibited ~100% corrosion coverage. In one exception (of the 6 controls) the corrosion coverage was only 30%. Material loss among the controls averaged ~ 15%. Material loss among the treated specimens was too small to measure.

3 PROCEDURES

This work focused on the nanoparticle treatment using a high current on a 3 inch x 6 inch concrete test cylinder. Figure 3 contains a flow chart of the experimental procedures used in this study. The nanoparticle chosen for the treatment was a 24-nm-diameter alumina-coated silica suspension (12 weight/percent content alumina). The nanoparticle suspension was provided by Nalco Chemical in Naperville, IL.

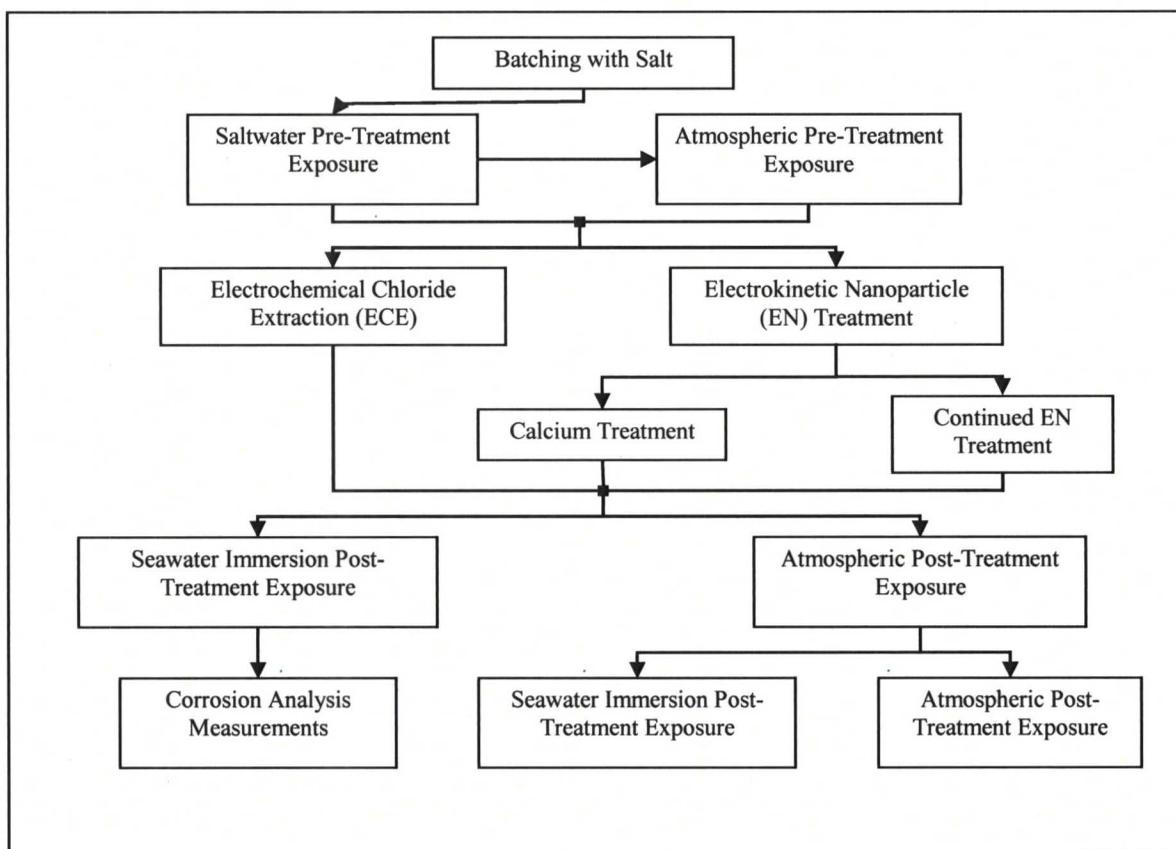


Figure 3. Experimental Flow Chart

3.1 Mix Design

The mix design was completed as per ACI 211.1, Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete. The mix ingredients in this case were Type I portland cement, aggregate, water, and salt. Pea gravel was obtained from TXI Inc. in Ruston, LA. The silica sand was acquired from Lowes, also in Ruston, LA. The salt was a reagent grade sodium chloride from Fisher Scientific in Pittsburgh, PA. Table 1 shows the batch composition. The material was poured into the test molds in three-volume increments as per ASTM C192, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory.

Table 1. Batch Composition

Materials	Weight (lbs)
Water	18.5
Cement	36.5
Gravel	93.5
Sand	56.5
Salt	0.83

3.2 Specimen Design

Figure 4 shows the schematic diagram of the front view of the specimen used in this research. The steel reinforcement inside the concrete was a 6-inch 1018 mild steel with a 0.25 inch diameter. The rebar was positioned in the center of the top of the specimen and 3 inches were embedded in the concrete. The material was poured into the molds in three-volume increments as per ASTM C192.

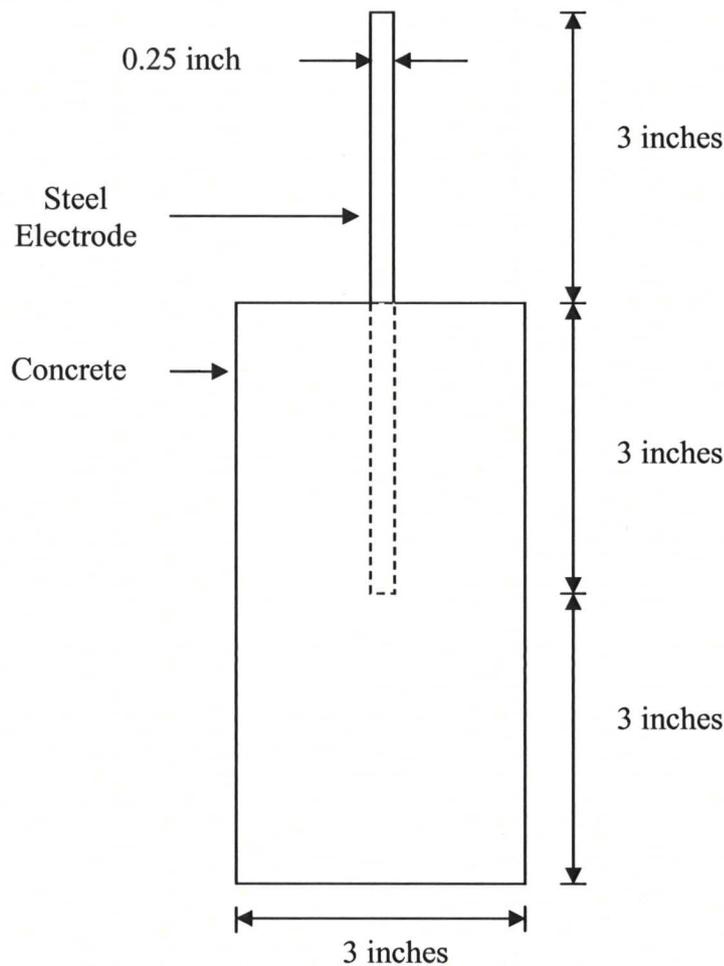


Figure 4. Schematic Drawing of Side View of Concrete Specimen

3.3 Concrete Specimen Development

After the concrete was poured and allowed to harden for 10 minutes, the steel rod was inserted into the concrete in the position shown in Figure 4. After 24 hours of curing, the specimens were removed from the plastic mold and placed in salt water (3.5% salt content) until treatment began on the specimen. Treatment of the first set of specimens began after 28 days of salt water pretreatment exposure. However, before treatment could be started, other preparations on the specimens needed to be made. First, a wire was threaded around the top of the rebar and placed between two nuts. An epoxy coating (Niles Chemical Paint, Company, Niles, MI) was applied to the top of the specimen and to the rebar that remained exposed, including the newly placed nuts and wire connection. The epoxy coating was provided to prevent any corrosion products from building up on the exposed rebar and wire connection and possibly influencing corrosion measurements. Figure 5 shows the specimen after the final preparations were completed. After these preparations were completed, the specimens were reimmersed in salt water to continue pretreatment exposure.



Figure 5. Concrete Cylinder Specimen Prior to Testing

3.4 Experimental Setup

The purpose of this research project was to see if it was possible to deliver the nanoparticles into the pores of the concrete using a high current density. This hypothesis was tested by setting the power supplies to produce a voltage drop across each specimen of 25 volts per inch of cover. In this case, there was 1.5 inches of cover so the desired voltage drop for one specimen needed to be 37.5 volts. Also, the current was checked daily during treatment to ensure that a current density of $10 \text{ A} / \text{m}^2$ was not exceeded. Three different treatment solutions were compared in this experiment: EN, EN + Ca, and ECE. A particle precipitation problem was observed during the EN treatment; so, in addition to the normal dilution of the nanoparticle suspension, some of the treatments utilized a super dilute nanoparticle suspension. Also, a comparison of a series and parallel treatment styles was tested.

In addition to the voltage and current measurements taken during treatment, electrical measurements were taken on the specimens. These additional measurements included a corrosion potential measurement and a corrosion rate measurement. The corrosion potential measurement was taken daily during the treatment and then weekly thereafter. Figure 6 shows the setup for a corrosion potential measurement.

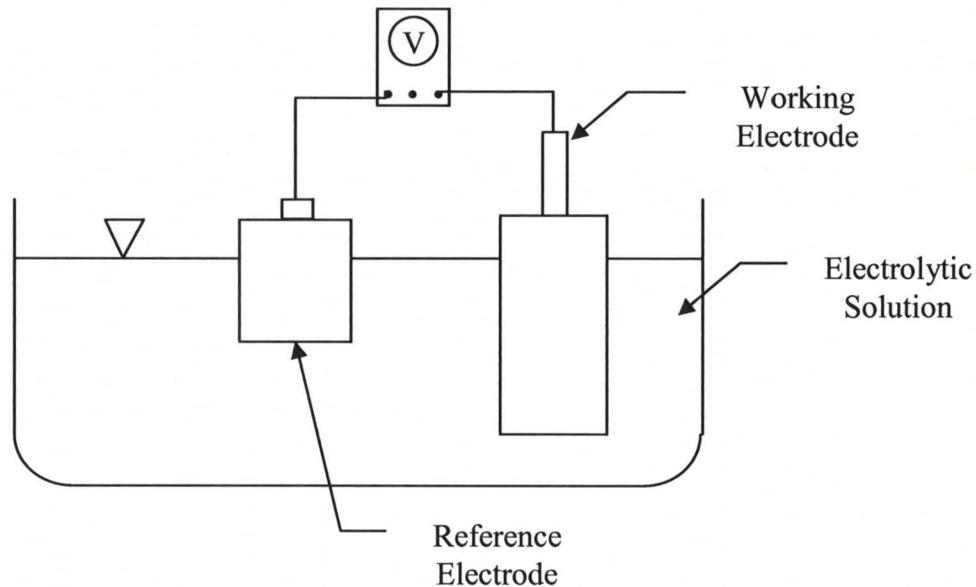


Figure 6. Setup for Corrosion Potential Measurement

The corrosion rate measurement was taken after the first, fourth, and seventh days of treatment. The corrosion rate was calculated by the linear polarization resistance method using a Gamry REF600 potentiostat.

3.5 Series Treatment Procedure

One style of treatment that was conducted involved connecting the specimens in series. This was accomplished by connecting two specimens per power supply (one EN and one ECE) and setting the power supply to produce a 37.5 volt drop across the EN-treated specimen. The circuit was connected so that the mixed metal oxide coated titanium counter electrode (CorrPro, Belle Chase, New Orleans, LA) of one specimen was connected to the positive terminal of the power supply, and the working electrode of the second specimen was connected to the negative terminal of the power supply. Figure 7 shows the circuit diagram for specimens connected in series.

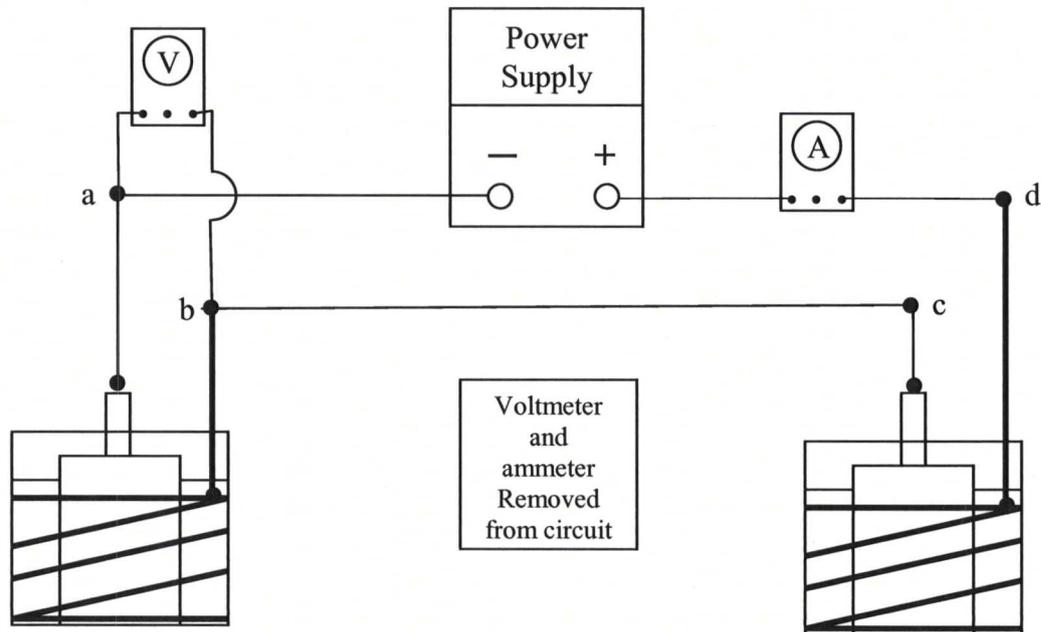


Figure 7. Circuit Diagram for Treatment of Specimens Connected in Series

The treatment of each specimen was completed in a 4 inch x 8 inch plastic mold. A mixed metal oxide coated titanium electrode was formed in a helical fashion around the inside of the treatment container. Figure 8 shows a schematic diagram of the specimen inside the treatment container.

The treatment container used was slightly larger than the specimen being treated so that a treatment suspension could be loaded into the annular space between the edge of the specimen and the inside of the container. This setup was arranged to promote a relatively uniform current distribution throughout the specimen so that the nanoparticles or chlorides could be delivered or removed evenly throughout the specimen. The treatment containers for each treatment type (EN, EN + Ca, or ECE) were similar. The treatment solutions or suspensions differed depending on the treatment being applied.

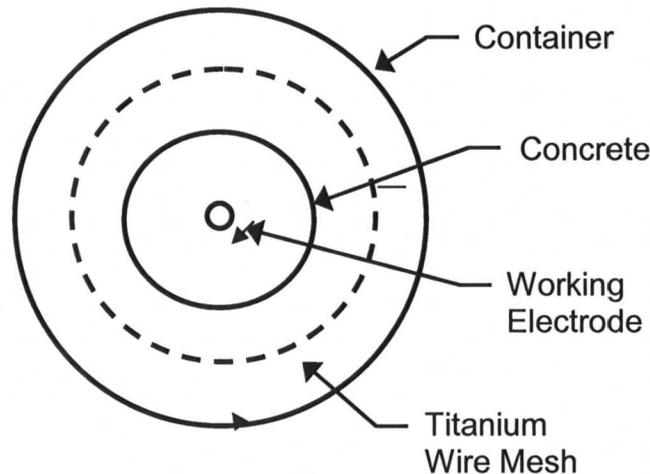


Figure 8. Top View of Treatment Container Setup for One Specimen

The EN-treated specimens had a certain dilution of nanoparticle solution. The more concentrated dilution included one part alumina coated silica suspension solution and two parts deionized water. The volume that was needed for the treatment of one specimen was 500 millimeter (mL). This solution was poured in the treatment container on the first day of treatment and was not removed until the treatment was complete. The less concentrated dilution included one part nanoparticle solution and 11 parts deionized water. The volume that was needed for the treatment of one specimen was also 500 mL; however, this solution was refreshed daily. Both dilutions were designed to provide equivalent particle dosage.

The specimens that received EN treatment plus an additional calcium treatment were very similar in treatment style to those that received only EN treatments. The EN + Ca specimens were treated with 4 days of either the normal dilute or super dilute nanoparticle suspensions. However, where they differ from the EN treatments is after the fourth day of treatment when the treatment solution was switched to a calcium nitrate tetrahydrate solution. Once again, the needed volume of treatment liquid was 500 mL. The calcium nitrate tetrahydrate treatment solution was made by dissolving 354 grams of calcium nitrate tetrahydrate in 1.5 liters of deionized water. This mixture was enough to supply three specimens with treatment solution.

The setup for the specimens designated to receive ECE treatment was very simple. The treatment solution volume was also 500 mL. This solution consisted of 10 grams of salt dissolved in 500 mL of deionized water. The salt was added as an electrolyte so that the resistance between the two electrodes did not become insurmountable. Figure 9 shows twelve specimens receiving treatment.

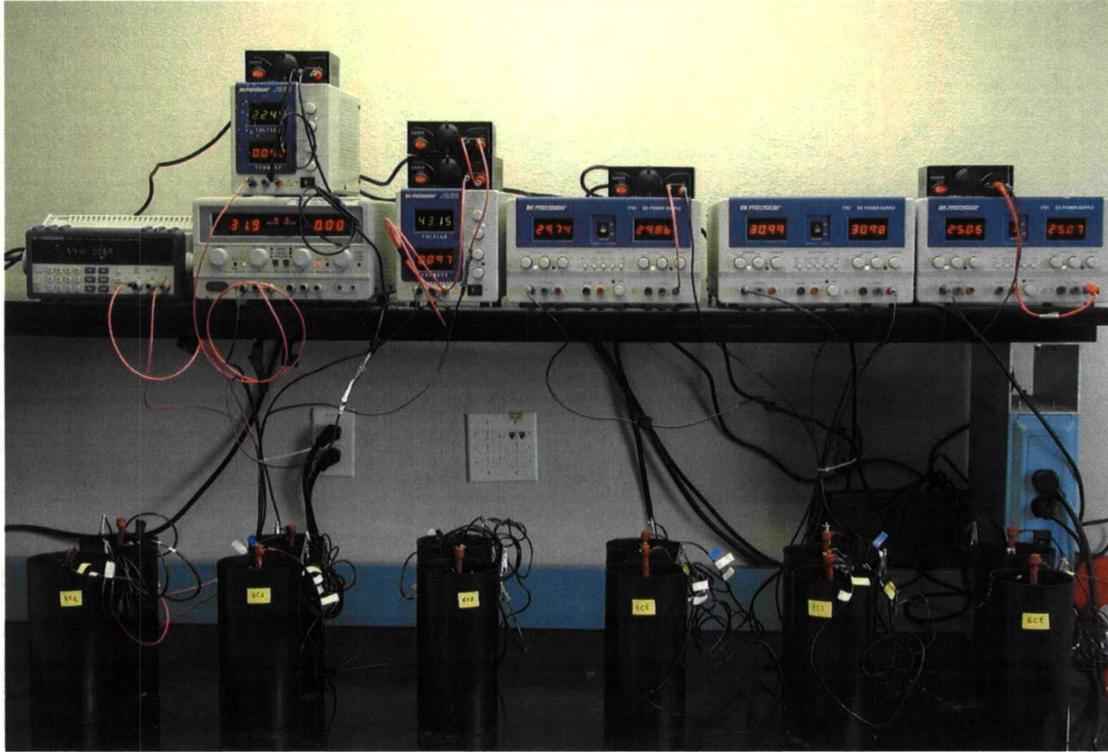


Figure 9. Treatment of Twelve Specimens Conducted in Series

3.6 Parallel Treatment Procedure

The second treatment type used in this experiment was connecting the specimens in parallel. The same parameters as in the series-treatment type were used for the parallel-treatment type. The power supplies were set to produce a voltage drop of 37.5 volts across the specimens, and the current was checked so as to not exceed 410 milliamperes (mA). This constituted a current density of 8.1 A/m^2 . In this case, all of the specimens that were receiving similar treatments were placed in one container rather than each specimen having its own treatment container. Similar to the series treatment setup, a titanium counter electrode was used to electrically push the nanoparticles into the pores of the concrete. Instead of the electrode going around the outside of the specimen, the electrode was placed in the center of the container, and the specimens organized around the electrode. The electrode was connected to the positive terminal on the power supply, and the node that was connected to the working electrode on the specimens was connected to the negative terminal. Figure 10 shows the circuit diagram for the parallel setup.

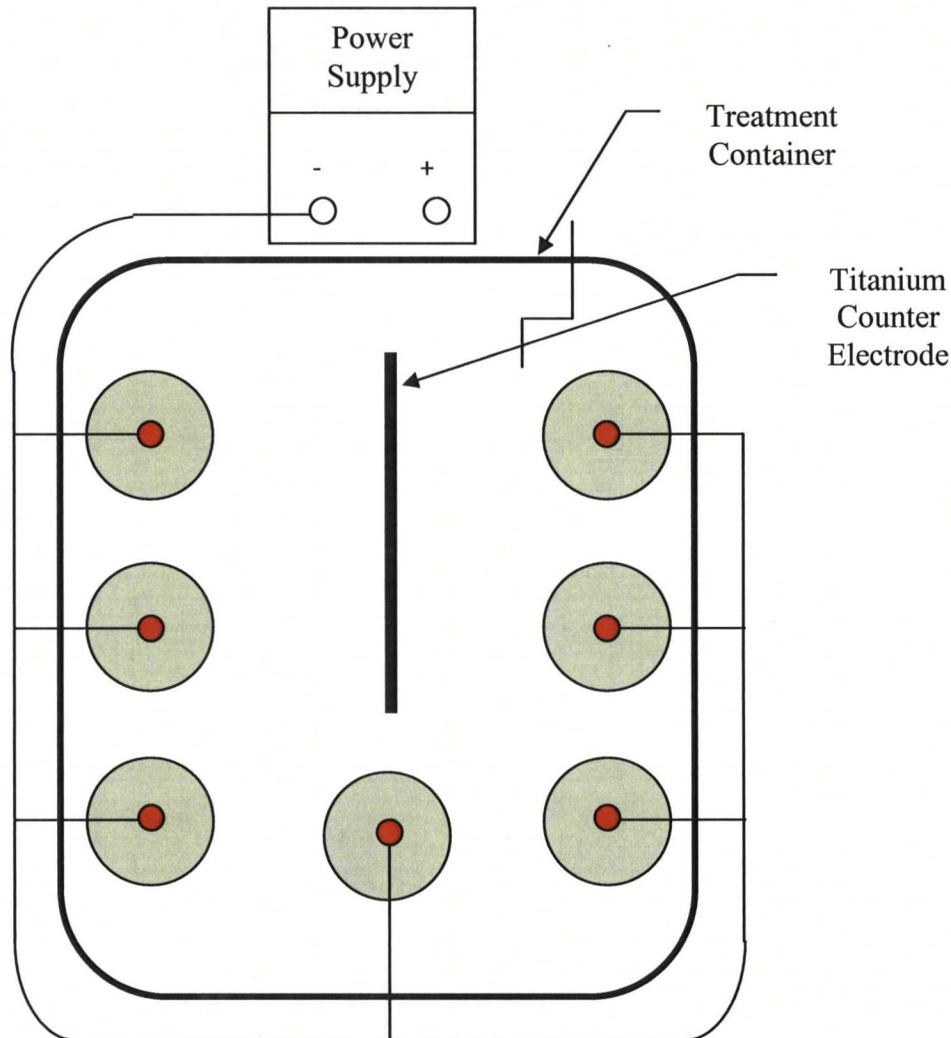


Figure 10. Setup for Parallel Treatment of Several Specimens (Top View)

All of the EN and EN + Ca specimens started out in one tub since both receive similar treatments for the first 4 days. After the fourth day, the EN specimens and EN + Ca specimens were placed in different treatment containers. When both specimen types were in the same container, the treatment solution that was used was similar to the super dilute solution used in the series setup. A ratio of 1 part alumina coated silica solution for 11 parts deionized water, which was refreshed daily, was used in this case. For the volume of container used, this solution included 0.27 liter (L) of nanoparticle suspension and 4.04 L of deionized water. After the fourth day of treatment, the EN specimens were separated from the EN + Ca specimens. The treatment suspension on the fourth day for the EN specimens included 0.16 L of nanoparticle solution and 4.16 L of deionized water. The treatment solution for the EN + Ca specimens included 217 g of tetra flake calcium chloride (Tetra Technologies, The Woodland, TX) in 4.31 L of deionized water.

The ECE specimens were treated in a container that was similar in setup to that of the EN container. A titanium electrode was placed in the middle of the container, and it was snaked from the bottom of the container to the top of the treatment solution multiple times. The solution that was placed in the remaining volume had 95 grams of sodium chloride (NaCl) and 4.31 L of deionized water. This solution remained as the solution for the duration of the treatment. Figure 11 shows an image of all of the containers during treatment.

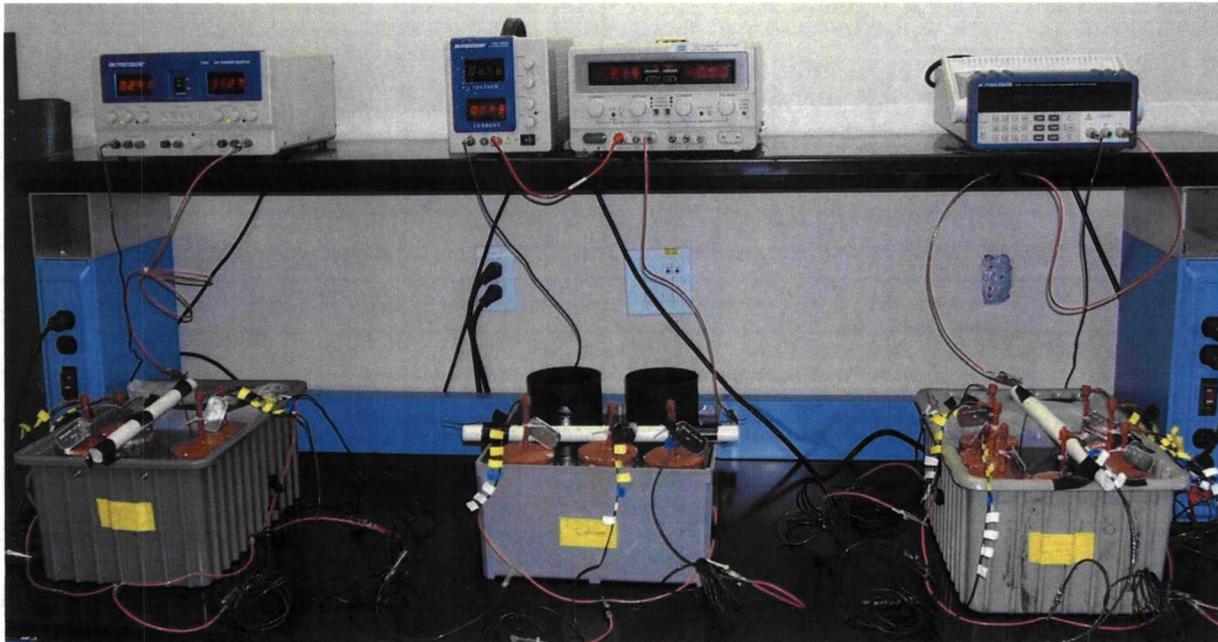


Figure 11. Treatment Setup Showing Specimens Arranged in a Parallel Treatment Circuit

3.7 Indirect Tension Test

An indirect tension test was performed on the pool specimens as per ASTM C 496-96. The purpose of this test was to compare the tensile strength of each treatment type (EN vs. EN + Ca vs. ECE vs. Controls). The strength influence of a steel bar within the specimen was examined in earlier work (Cardenas and Goli, 2006). As a conclusion from this earlier work, a specimen with a steel reinforcement and a specimen with a hole of the same size at the same location had approximately the same strength value.

This test method consists of the application of a diametrical compressive force distributed along the length of the cylinder at a rate of 150 psi/min until failure. The loading induces tensile stress, σ , on the plane through which the applied load acts. The tensile strength can be obtained from the equation shown in Figure 12 where P is the maximum load applied before failure, L is the length of the specimen, and D is the diameter of the specimen.

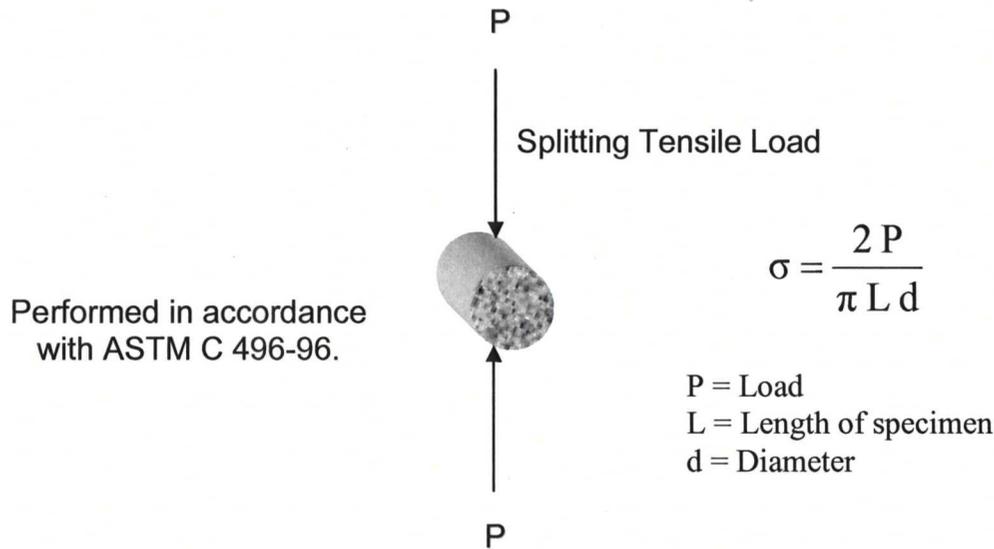


Figure 12. Indirect Tensile Splitting Tensile Strength Test

3.8 Results and Discussion

This section deals with relatively young concrete specimens field tested in waterline, seawater immersion for a short period of 30 days. Following initial saltwater exposure these specimens were subjected to electrokinetic nanoparticle treatment. Following treatment, the specimens were returned to the seawater immersion tank for a period of 30 days. At this point the specimens were subjected to corrosion evaluation. This evaluation included destructive tensile strength testing. Immediately following fracture, the steel reinforcement of each specimen was examined to determine the extent of corrosion product coverage. This evaluation was conducted before and after treatment.

Figure 13 contains a bar chart illustrating the measured surface areas that were covered with corrosion products. Each column represents a specific test category. Four to six specimens were tested in each of these categories. The value reported for each column is an average of these specimens. The first column on the left represents the controls examined just prior to treatment application. The 3% corrosion coverage occurred over a 21-day exposure period. The remaining columns represent specimens that were tested following EN treatment and a 30-day post-treatment waterline exposure to saltwater. The EN-treated specimens exhibited 6% average corrosion coverage while the EN + Ca case revealed 4% average corrosion coverage. The specimens subjected to chloride extraction without particle treatment exhibited an 11% area of corrosion coverage. The control specimens were not subjected to any treatment. These exhibited an average corrosion area coverage of 67%. Some pitting corrosion was also observed.

The error bars associated with this data indicate that corrosion products present following treatment and 30 days of seawater exposure were not significantly different from the controls that were examined just prior to treatment. This suggests that the initial corrosion did not

significantly progress shortly after treatment started. Based on these observations, it appears that the nanoparticle treatments were successful in mitigating further corrosion damage.

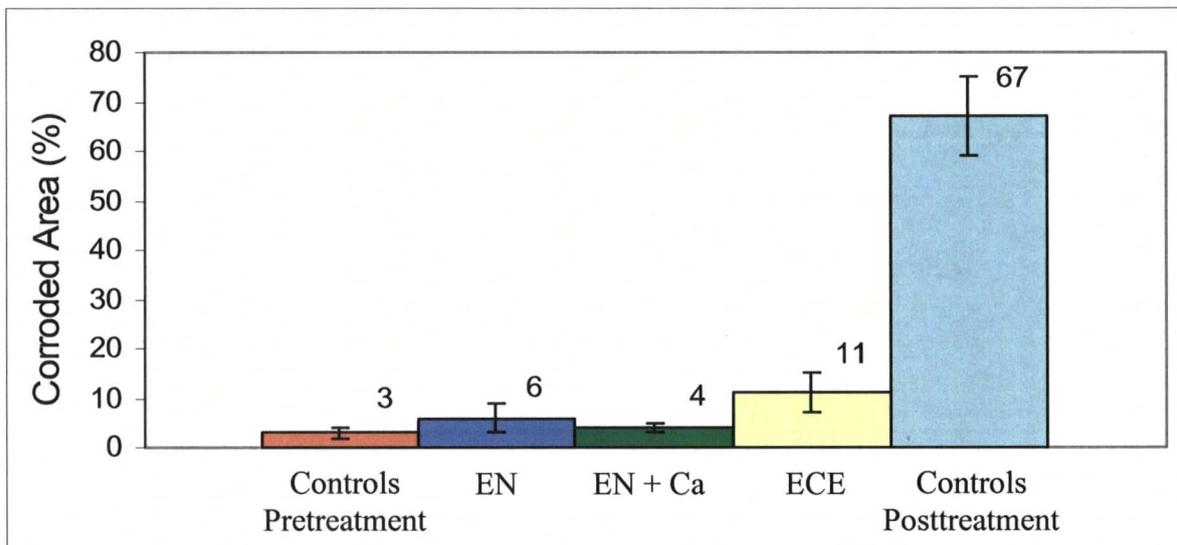


Figure 13. Corrosion Analysis That Compares the Measured Area Covered With Corrosion Products for Each Case

The error bars also indicated no overlap between the EN + Ca specimens and those specimens that were subjected to ECE only. The ECE corrosion rate was also apparently distinct from the control specimens just prior to treatment. These observations indicate that EN treatment with and without a calcium post-treatment was effective in retarding the return migration of chlorides shortly after treatment while all the specimens were immersed in saltwater.

The area of corrosion coverage among the untreated control specimens was 6 to 15 times greater than that of any of the other cases. This indicates that the environment was significantly aggressive. It also indicates that all three treatments were successful in reducing the corrosion rate of the specimens.

Figure 14 shows 4 bars that were removed from the control pretreatment. These specimens clearly exhibited areas of active corrosion. The 3% corrosion coverage reported in Figure 13 was obtained from these specimens.

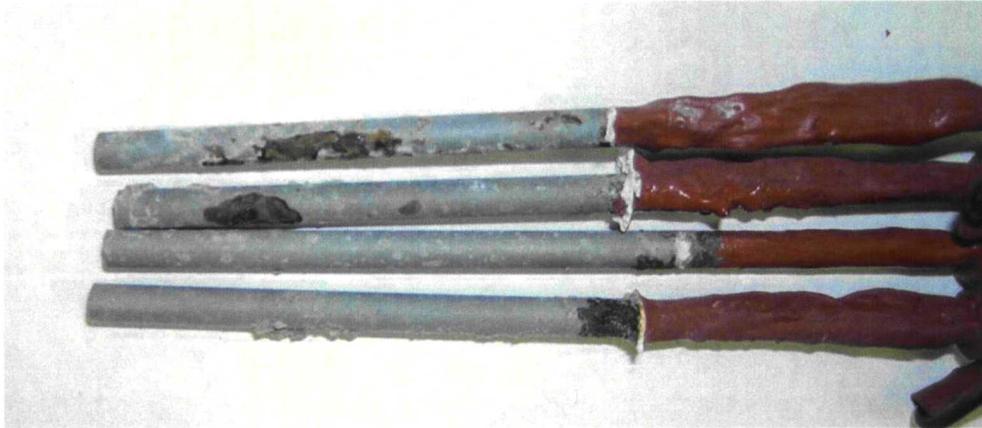


Figure 14. Left Side of Each Specimen Shows the Area Corroded During the Course of Aggressive Saltwater Exposure

Figure 15 shows a comparison of the other cases represented in the bar chart of Figure 13. Each specimen represents the worst case observed in each category. The control specimen at the top of the figure exhibited 100% corrosion coverage and evidence of pitting. The ECE specimen exhibited extensive corrosion damage with some pitting. The EN and EN + Ca specimens also exhibited some corrosion.

The specimens comparing ECE to the two EN treatments clearly showed less corrosion observed among the EN-treated cases. The difference in corrosion coverage between these and the control was also evident. In comparing these cases to the pretreatment specimens of Figure 14 it is apparent that the control and the ECE cases (Figure 15) exhibited more severe corrosion than the pretreatment controls. The distinction between the two EN cases and the pretreatment controls was not readily apparent. These visual observations of the worst cases in each category appear to reflect the same order of severity that is observed in the bar chart of Figure 12 where the EN cases and the pretreatment controls are generally hard to distinguish, and the ECE and controls are clearly the worst cases. These observations indicate that the EN and ECE treatments appeared to halt the corrosion progress. The EN + Ca treatments did not appear to stand out. Perhaps a longer exposure period will possibly show differences in performance among these cases.

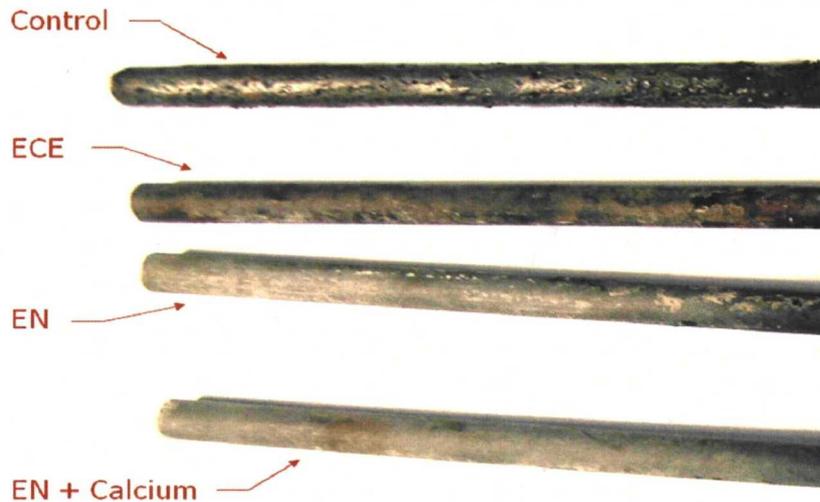


Figure 15. Comparison of Corroded Area Coverage for Each Case Considered in This Study

The results of the tensile tests carried out are illustrated in the bar chart of Figure 16. The lowest values were observed among the untreated controls. These values were over 30% below the values obtained for the EN-treated specimens. The EN + Ca and the ECE-treated specimens exhibited values of 221 and 219 psi respectively.

In Figure 16 it is clear that the EN-treated specimens were significantly stronger in tension than the untreated controls. This strength enhancement has two likely sources. The first source is the porosity reduction due to EN-treatment. Reductions in porosity induced by this work provided enhanced strength. In addition, the more extensive corrosion damage observed on the surfaces of the control specimens could have contributed to the lower strength result since the buildup of corrosion products on the bars could have caused the development of tensile residual stresses. This stress may have added to the stress present during the course of tensile testing, leading to a lower apparent strength.

It is notable that the error bars in all cases are larger than what is generally expected for concrete testing. For this reason the distinction between the three treated cases is not very significant. This unusual extent of scatter may be due to the presence of the steel bars in each specimen. A slight departure from vertical positioning of the bar could have yielded a significant reduction in strength. This is because a misaligned bar would tend to cross through the plane of fracture that develops at the point of failure. This crossover could tend to increase the value of a given result since the two sides of the specimen would be slightly harder to separate.

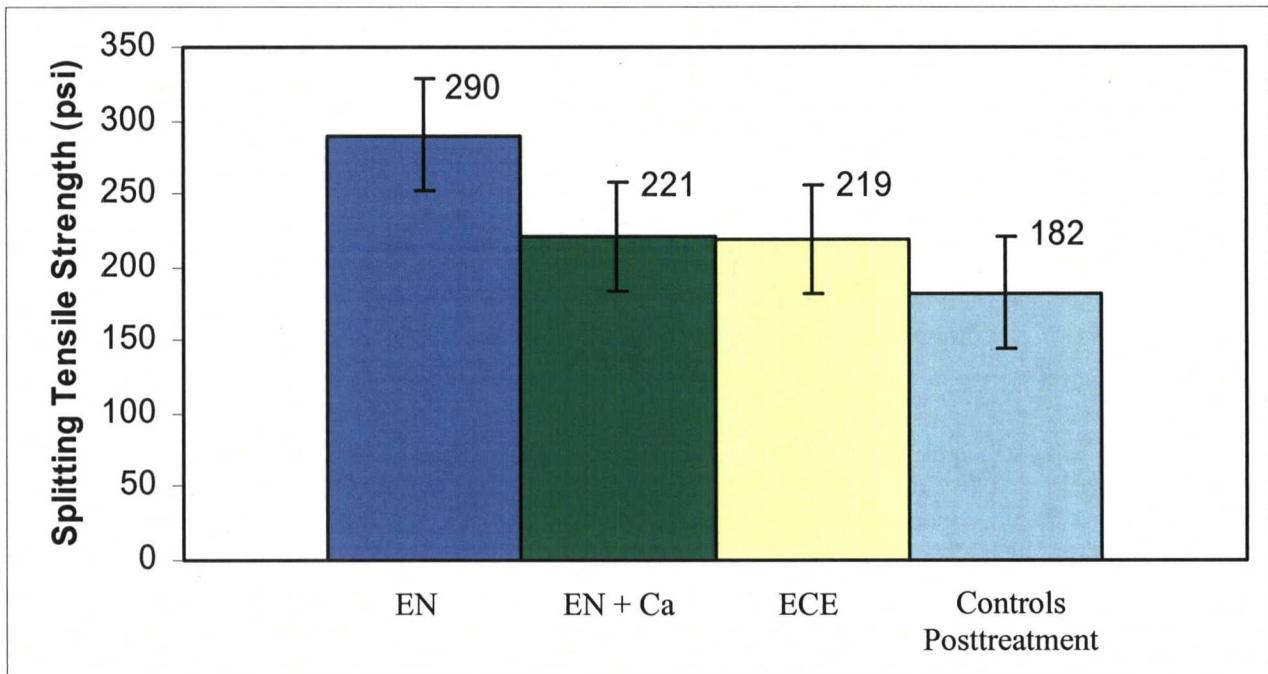


Figure 16. Comparison of Splitting Tensile Strength for Each Treatment Case

During a given treatment, the degree to which the treatment circuit experiences a rise in resistance can be taken as a measure of treatment success. This is because the particles carry a portion of the electric current. When a particle is lost due to reaction or coagulation, its contribution to the conductivity of the circuit is also removed. With fewer current conductors available to pass the current, the resistance of the circuit is expected to rise. Figure 17 illustrates an example of the general trend in current that was delivered. In each case the current density was reduced by at least 50%. In prior work, it was observed that a successful treatment was associated with 20 percent reductions in current density and significant porosity reductions (Cardenas 2002). Based on these observations and comparison with prior work, it appears that each of the treatments conducted on immersion tank specimens was sufficient to produce a measurable impact on the microstructure and durability of the specimens.

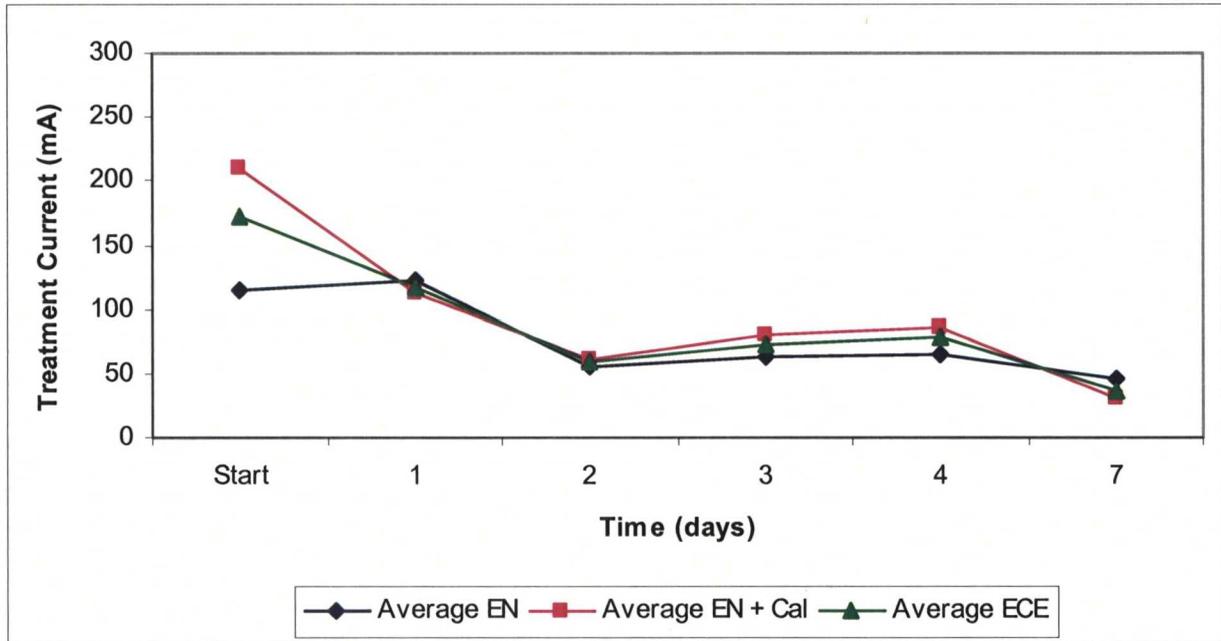
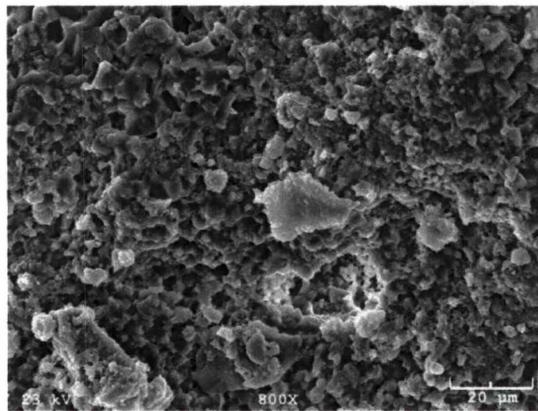
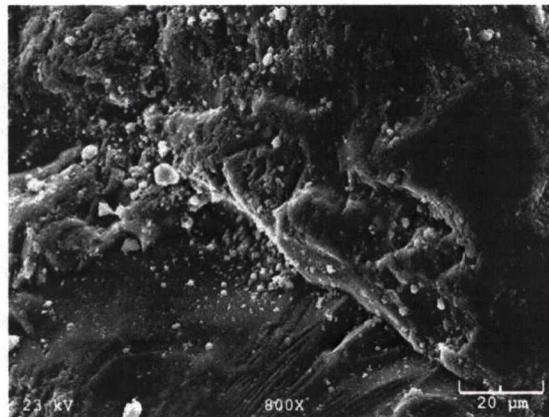


Figure 17. Treatment Current During Nanoparticle Application

The microstructure of these specimens was examined following tensile strength testing. Figure 18 provides a comparison in microstructure of the EN-treated and ECE-treated cases. The ECE-treated specimen appears to exhibit a typical porous morphology for hardened cement paste at a fracture surface. The EN specimen image contains a fairly dense aggregate particle evident in 75% of the image. The upper left quadrant appears to contain cement paste. The morphology of this paste appears to be denser than that observed in the ECE case.



ECE Specimen



EN Specimen

Figure 18. SEM Images of ECE and EN Specimens at a Distance of 1 mm From the Steel Reinforcement

A more extensive example of this densified morphology is shown in Figure 19. These samples were removed from a specimen subjected to EN treatment for 4 days followed by 3 days of calcium treatment. Both images clearly show the light-colored florets of a calcium-rich phase. The right side image also provides a clearer view of the densified cement morphology that is typical of EN treatment. As shown in the chart in Figure 16, the calcium contribution did not appear to enhance the strength of the cylinders as compared to the EN treatment alone.

These SEM samples resided from the steel reinforcement at a distance of approximately 1 mm. Based on the dosages of the treatments applied, the extent of the treated zone would be expected to range as much as 12 to 25 millimeter (mm) from the steel. It is thus not surprising that the image of the EN-treated sample would exhibit a densified morphology at a distance of 1 mm from the steel. In Figure 16, the differences in tensile strength observed in these cases exhibited some overlap as indicated by the respective error bars. Despite this small overlap, the ~25% average difference in strength between ECE and EN cases was notable. As indicated by the SEM images shown on Figures 18 and 19, the most likely cause for this strength increase was a porosity reduction due to nanoparticle loading of the capillary pore network in the concrete.

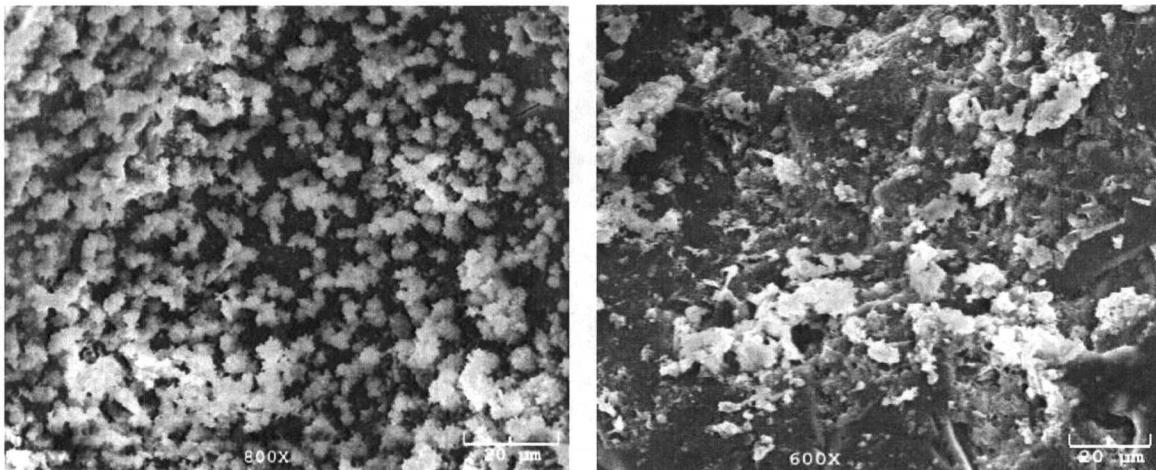


Figure 19. SEM Image of EN + Ca Treated Specimen Showing Light-Colored Calcium-Rich Deposits (Samples Taken 1 mm From the Steel Reinforcement)

Each of the treatments shared chloride extraction as a common feature. In the cases of the nanoparticle treatments, the delivery of particles in extraction of chlorides out was designed to be simultaneous. The chloride content was examined by Energy Dispersive X-Ray Spectroscopic (EDS) analysis of polished SEM specimens. Figures 20 and 21 contain images of EN treated and EN + Ca treated specimens after they had been reimmersed in saltwater for 30 days. The images exhibit relatively dark regions of aggregate surrounded by lighter regions of hardened cement paste. Occasional black areas are large pores or voids. In some cases a particle of concrete became lodged in these pores (as indicated by a lighter color within them). The EDS analysis was conducted on these polished surfaces in order to obtain quantitative information on the elemental content of the microstructures. The chart of peaks indicating the presence of various species appears to the right of each polished image.

Table 2 contains the elemental composition results obtained from specimens representing each category of this study. It was observed that the controls exhibited the most sodium and chloride. The two EN cases exhibited the most aluminum. The EN + Ca cases exhibited the highest calcium content. The highest silicon content observed was in the controls category.

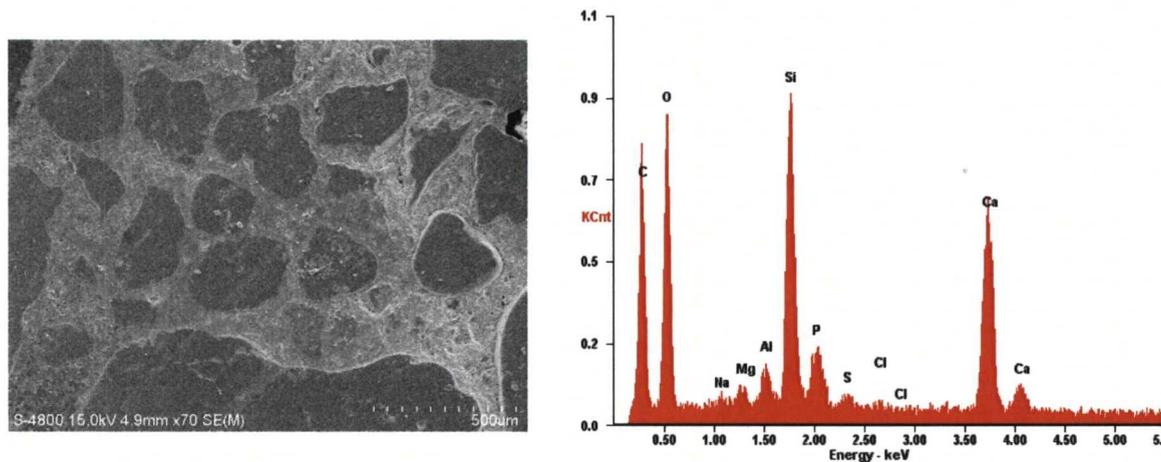


Figure 20. SEM Image of Polished Concrete Specimen (Left) and EDS Analysis (Right)

NOTE

The specimen was subjected to EN treatment. Dark regions are aggregate particles. The lighter regions are hardened cement paste.

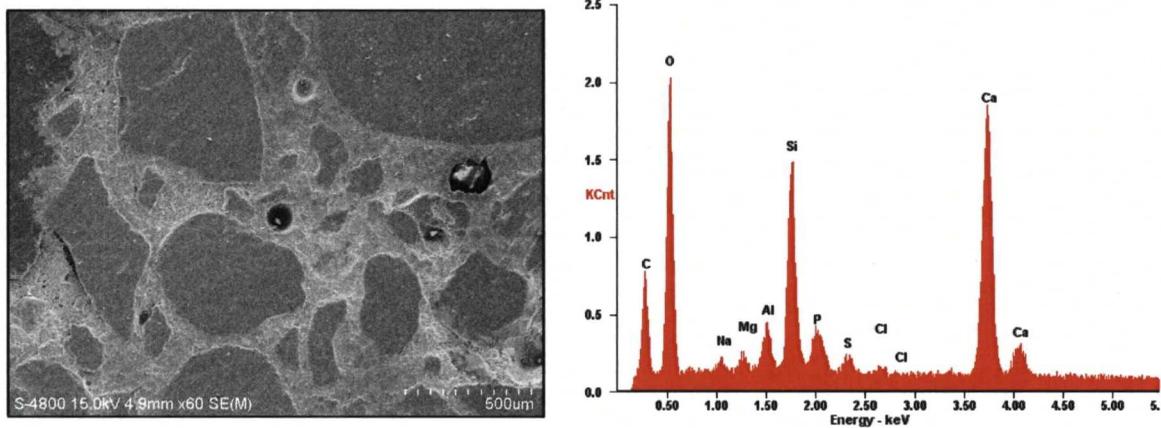


Figure 21. SEM Image of Polished Concrete Specimen (Left) and EDS Analysis (Right)

NOTE

The specimen was subjected to EN treatment for 4 days followed by a calcium ion treatment for 3 days (EN + Ca). The black areas are large pores. Lighter regions within the pores are probably debris particles that were introduced during the sectioning process.

Table 2. Elemental Composition Results From SEM/EDS Analysis

Specimen Type	Cl*	Na	Al	Ca	Si
Controls	4.1	3.2	1.0	10.9	23.8
EN	0.0	0.3	1.1	14.8	10.0
EN + Calcium	0.4	0.5	1.7	23.7	5.6
ECE	0.8	0.5	0.6	8.5	1.0

*Each amount reported as wt. % of the sample.

Of all the species listed in Table 2, the only ones that are not common to concrete are the sodium and chloride. The elevated sodium and chloride content of the controls is not surprising since these species are dominant in saltwater, and there was no pore-blocking treatment applied in these cases that could stop the ingress of these species.

It is interesting to note that none of the cases exhibited an unusually high aluminum content. Apparently, alumina-coated silica particles did not carry a large abundance of aluminum. The calcium content was understandably elevated in the EN + Ca case.

The silicon content results are somewhat puzzling. The silicon content in hardened cement paste and many aggregates was expected to be reasonably significant. EN treatment would be expected to provide additional silicon but this value was decidedly smaller for the two EN cases 10 and 5.6 weight % as compared to the 23.8 wt. % content of the untreated control. The near-zero silicon content of the ECE case is also puzzling.

Table 3 contains a list of corrosion rates obtained from several control specimens subjected to saltwater immersion. The average value from this set is 0.41 mils per year (mpy). These values were obtained just prior to the initiation of treatments. Table 4 contains corrosion rates measured after the initiation of EN and ECE treatments. As compared to the pretreatment values, the corrosion rates after 1 day of treatment were generally over 200% higher than the pretreatment values.

Table 3. Corrosion Rates Measured Prior to Treatment

Specimen	Corrosion Rate (mpy)
1	0.30
2	0.1.1
3	0.5
4	0.72
5	0.58
6	0.64
7	0.49
8	0.27
9	0.29
10	0.26
11	0.12
12	0.27
13	0.11
15	0.98
16	0.30
17	0.19
18	0.62
29	0.71

On the 4th day following the start of an EN treatment, the corrosion rates were higher. The corrosion rates for EN and EN + Ca were 30% and 40% lower on average than day 1. By day 7, these rates were up to 200 and 270% higher respectively.

The increase in corrosion rate observed after day 1 for all cases may have been due to the collection of positively charged ions at the electrode. These ions (typical of concrete) include sodium, calcium, and potassium. When these ions are electrochemically gathered at an electrode, the coated electrode behaves as a rapidly corroding material in which the products of corrosion are various oxidation states of sodium, potassium, calcium ions, and molecules. Each time the EN or ECE treatment pauses, these species form the basis of a rapid corrosion current. Thus, while the electrode is corroding, the products of corrosion do not include iron. Interestingly, by day 4, the corrosion rates for the EN cases dropped while those for the ECE case rose. At the same time, it was anticipated that the first of the nanoparticles would arrive at the electrode after 1 day of treatment. If the particles are able to block the access of chlorides, it then stands to reason that they could be used to block the dissolution of sodium, potassium, and calcium. This may explain why the apparent corrosion rate drops off by day 4 in these cases while the ECE exhibited a 16% increase. By day 7, the nanoparticles had long since arrived. The new arrivals may simply be additional ions that are falling in behind the nanoparticle layer. These new species layers could be providing the high-corrosion rates as they too come back off the now layered chemistry of the electrode.

Table 4. Corrosion Rates Measured During Treatment Period

Treatment Type	Corrosion Rate after 1 day (mpy*)	Corrosion Rate Change, Day 4 (%)	Corrosion Rate Change, Day 7 (%)
EN	1.34	-30.1	+199.8
EN + Cal	1.73	-40.9	+267.4
ECE	1.80	+16.2	+337.6

*mpy = mils per year

Figure 22 contains a plot comparing the corrosion rates measured during the course of treatment. These are compared also to the electric currents used to apply the treatments. In each case the curves generally were trending downward. The EN cases appeared to be clustered together while the ECE case tended to form a separate (yet still downward) trend with much higher corrosion rates. It is conceivable that the EN particles may be forming a layer that somewhat inhibits the dissolution of the collection of sodium, potassium, and calcium ions.

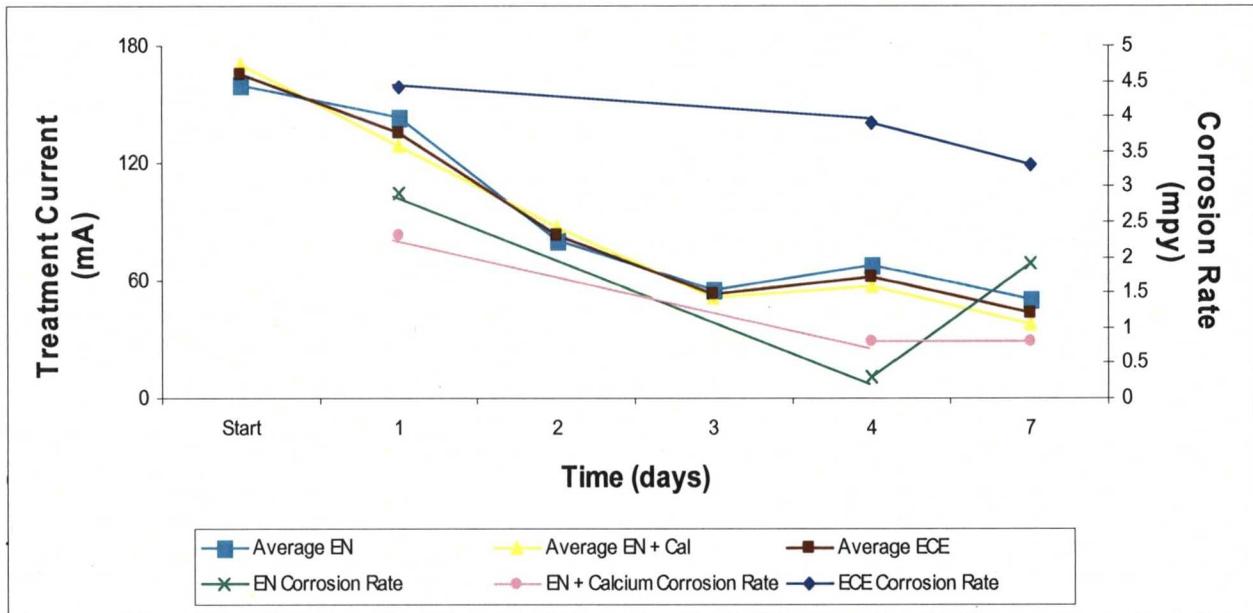


Figure 22. Comparison of Treatment Current and Corrosion Rate During Nanoparticle Treatment Application Period for Immersion Specimens

4 CONCLUSIONS

The nanoparticle treatments were successful in stopping corrosion damage to the steel reinforcement after it had already started.

These observations indicate that EN treatment with and without a calcium posttreatment was impeding the return migration of chlorides.

The EN-treated specimens were significantly (25 – 30%) stronger in tension than the untreated controls. This strength enhancement has two likely sources. The first source is the porosity reduction due to EN treatment. Reductions in porosity induced by this work provided enhanced strength. The second source is the more extensive corrosion damage observed on the surfaces of the control specimens. This corrosion that could have contributed to the lower strength result for the controls, since the buildup of corrosion products on the bars could have caused the development of tensile residual stresses. This residual stress may have added to the stress present during the course of tensile testing, leading to a lower apparent strength for the controls.

The elevated sodium and chloride content of the untreated controls was not surprising since these species are dominant in saltwater, and there was no pore-blocking treatment applied in these cases that could stop the ingress of sodium and chloride.

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APPENDIX A. CORROSION POTENTIALS

A.1 Corrosion Potentials for Pool Specimens

Table 5. Corrosion Potentials for Specimens 1-28, 59-66

Specimen #	Treatment Type	6/19/2008	6/20/2008	6/23/2008	6/24/2008	6/25/2008	6/26/2008
1	Controls	-0.265	-0.266	-0.262	-0.259	-0.249	-
2	Controls	-0.128	-0.138	-0.158	-0.172	-0.164	-
3	Controls	-0.304	-0.307	-0.314	-0.318	-0.322	-
4	Controls	-0.251	-0.255	-0.252	-0.253	-0.242	-
5	EN + Calcium	-0.257	-0.266	-0.276	-0.290	-0.282	-0.292
6	EN + Calcium	-0.233	-0.231	-0.234	-0.240	-0.228	-0.233
7	EN + Calcium	-0.250	-0.254	-0.243	-0.246	-0.243	-0.246
8	EN	-0.293	-0.288	-0.292	-0.293	-0.286	-0.292
9	EN	-0.225	-0.233	-0.236	-0.236	-0.228	-0.226
10	ECE	-0.299	-0.304	-0.311	-0.314	-0.309	-0.312
11	ECE	-0.274	-0.278	-0.284	-0.287	-0.275	-0.279
12	ECE	-0.157	-0.152	-0.158	-0.165	-0.147	-0.156
13	ECE	-0.155	-0.150	-0.136	-0.126	-0.112	-0.112
14	ECE	-0.271	-0.267	-0.271	-0.252	-0.254	-0.265
15	Controls	-0.324	-0.337	-0.342	-0.342	-0.340	-0.346
16	Controls	-0.272	-0.269	-0.260	-0.258	-0.252	-0.256
17	Controls	-0.227	-0.232	-0.253	-0.254	-0.243	-0.245
18	Controls	-0.302	-0.315	-0.333	-0.343	-0.343	-0.355
19	EN + Calcium	-0.271	-0.271	-0.268	-0.940	-0.958	-0.972
20	EN + Calcium	-0.243	-0.242	-0.247	-0.960	-0.980	-0.992
21	EN + Calcium	-0.247	-0.245	-0.242	-1.090	-0.980	-1.045
22	EN	-0.146	-0.104	-0.154	-0.970	-0.920	-0.972
23	EN	-0.281	-0.286	-0.291	-0.900	-0.990	-0.975
24	ECE	-0.321	-0.324	-0.335	-0.930	-0.950	-0.988
25	ECE	-0.449	-0.447	-0.436	-0.960	-0.950	-1.004
26	ECE	-0.256	-0.258	-0.259	-0.960	-0.950	-1.013
27	ECE	-0.259	-0.260	-0.255	-0.980	-0.940	-1.138
28	ECE	-0.291	-0.291	-0.298	-0.790	-0.890	-0.936
59	Controls	-0.045	-0.045	-0.100	-0.053	-0.036	-0.043
60	Controls	-0.355	-0.358	-0.365	-0.365	-0.360	-0.367
61	EN	-0.278	-0.272	-0.262	-0.256	-0.251	-0.255
62	ECE	-0.279	-0.281	-0.283	-0.280	-0.274	-0.284
63	Controls	-0.335	-0.336	-0.336	-0.318	-0.324	-0.333
64	Controls	-0.257	-0.255	-0.246	-0.238	-0.235	-0.241
65	EN	-0.277	-0.279	-0.286	-1.020	-1.000	-0.997
66	ECE	-0.231	-0.229	-0.224	-0.990	-1.017	-1.047

Table 5. Corrosion Potentials for Specimens 1-28, 59-66 (Continued)

Specimen #	Treatment Type	6/27/2008	6/30/2008	7/1/2008	7/2/2008	7/3/2008	7/7/2008
1	Controls	-	-	-	-	-	-
2	Controls	-	-	-	-	-	-
3	Controls	-	-	-	-	-	-
4	Controls	-	-	-	-	-	-
5	EN + Calcium	-0.279	-0.292	-1.086	-1.063	-0.978	-0.940
6	EN + Calcium	-0.217	-0.240	-1.046	-1.056	-0.974	-0.904
7	EN + Calcium	-0.239	-0.253	-1.026	-1.046	-0.980	-0.854
8	EN	-0.278	-0.287	-1.029	-1.100	-1.061	-0.700
9	EN	-0.216	-0.220	-1.025	-1.049	-0.955	-0.540
10	ECE	-0.301	-0.306	-0.976	-1.091	-0.979	-0.948
11	ECE	-0.263	-0.276	-0.972	-1.014	-0.971	-0.907
12	ECE	-0.195	-0.181	-0.992	-1.097	-0.991	-0.883
13	ECE	-0.096	-0.112	-0.986	-1.030	-0.977	-0.717
14	ECE	-0.241	-0.240	-1.283	-1.003	-0.975	-0.761
15	Controls	-0.332	-	-	-	-	-0.331
16	Controls	-0.241	-	-	-	-	-0.258
17	Controls	-0.242	-	-	-	-	-0.301
18	Controls	-0.354	-	-	-	-	-0.286
19	EN + Calcium	-1.015	-0.940	-	-	-	-0.725
20	EN + Calcium	-0.947	-0.940	-	-	-	-0.778
21	EN + Calcium	-0.966	-0.870	-	-	-	-0.736
22	EN	-0.948	-0.590	-	-	-	-0.175
23	EN	-0.960	-0.910	-	-	-	-0.749
24	ECE	-0.930	-0.920	-	-	-	-0.542
25	ECE	-0.953	-0.940	-	-	-	-0.773
26	ECE	-0.933	-0.890	-	-	-	-0.193
27	ECE	-	-0.830	-	-	-	-0.729
28	ECE	-0.856	-0.760	-	-	-	-0.071
59	Controls	-0.027	-	-	-0.046	-	-
60	Controls	-0.350	-	-	-0.359	-	-
61	EN	-0.242	-0.223	-1.018	-1.046	-0.858	-0.272
62	ECE	-0.275	-0.275	-0.998	-1.009	-0.926	-0.699
63	Controls	-0.320	-	-	-0.320	-	-
64	Controls	-0.219	-	-	-0.229	-	-
65	EN	-0.956	-0.010	-	-	-	-0.779
66	ECE	-0.965	-0.640	-	-	-	-0.769

Table 5. Corrosion Potentials for Specimens 1-28, 59-66 (Continued)

Specimen #	Treatment Type	7/17/2008	7/24/2008	7/28/2008	8/8/2008
1	Controls	-	-	-	-
2	Controls	-	-	-	-
3	Controls	-	-	-	-
4	Controls	-	-	-	-
5	EN + Calcium	-	-0.761	-0.764	-
6	EN + Calcium	-0.760	-0.752	-0.749	-
7	EN + Calcium	-0.749	-0.743	-0.745	-
8	EN	-0.744	-0.735	-0.646	-
9	EN		-0.754	-0.717	-
10	ECE	-0.760	-0.727	-0.605	-
11	ECE	-0.770	-0.733	-0.603	-
12	ECE		-0.749	-0.736	-
13	ECE	-0.713	-0.747	-0.746	-
14	ECE	-0.763	-0.726	-0.756	-
15	Controls	-0.316	-0.307	-0.317	-0.074
16	Controls	-0.271	-0.288	-0.289	-0.206
17	Controls	-0.320	-0.311	-0.320	-0.001
18	Controls	-0.284	-0.285	-0.302	-0.070
19	EN + Calcium	-0.746	-0.739	-0.715	-
20	EN + Calcium	-0.738	-0.728	-0.588	-
21	EN + Calcium	-0.758	-0.751	-0.725	-
22	EN	-0.173	-0.044	-0.044	-
23	EN	-0.556	-0.749	-0.741	-
24	ECE	-	-0.069	-0.074	-
25	ECE	-0.754	-0.712	-0.562	-
26	ECE	-	-0.252	-0.244	-
27	ECE	-0.239	-0.722	-0.385	-
28	ECE	-	-0.083	-0.135	-
59	Controls	-0.026	-0.021	-0.056	-0.025
60	Controls	-0.026	-0.305	-0.312	-0.298
61	EN	-0.682	-0.480	-0.216	-
62	ECE	-	-0.046	-0.064	-0.016
63	Controls	-0.293	-0.280	-0.279	-0.298
64	Controls	-0.300	-0.291	-0.284	-0.285
65	EN	-0.700	-0.606	-0.553	-
66	ECE	-0.725	-0.397	-0.042	-0.022

All potentials reported with reference to S.H.E. and in units of volts.

A.2 Corrosion Potentials for Complex 20 Specimens**Table 6. Corrosion Potentials for Specimens 29-40, 67-78**

Specimen #	Treatment Type	6/19/2008	6/20/2008	6/23/2008	6/24/2008	6/25/2008	6/26/2008
29	Controls	-0.389	-0.395	-0.402	-0.404	-0.406	-0.412
30	Controls	-0.256	-0.242	-0.197	-0.156	-0.111	-0.114
31	EN	-0.298	-0.310	-0.355	-0.360	-0.367	-0.387
32	EN	-0.312	-0.312	-0.338	-0.337	-0.332	-0.343
33	ECE	-0.280	-0.286	-0.304	-0.258	-0.240	-0.245
34	ECE	-0.353	-0.382	-0.357	-0.353	-0.346	-0.353
35	Controls	-0.056	-0.116	-0.113	-0.093	-0.091	-0.088
36	Controls	-0.326	-0.325	-0.334	-0.331	-0.330	-0.335
37	EN + Calcium	-0.181	-0.168	-0.223	-0.257	-0.282	-0.279
38	EN + Calcium	-0.403	-0.401	-0.387	-0.384	-0.348	-0.365
39	ECE	-0.250	-0.253	-0.259	-0.256	-0.253	-0.254
40	ECE	-0.281	-0.278	-0.298	-0.297	-0.300	-0.307
67	Controls	-0.355	-0.361	-0.374	-0.366	-0.366	-0.370
68	Controls	-0.293	-0.289	-0.297	-0.290	-0.277	-0.286
69	EN	-0.240	-0.238	-0.236	-0.239	-0.244	-0.242
70	EN	-0.256	-0.259	-0.261	-0.257	-0.253	-0.251
71	ECE	-0.285	-0.282	-0.285	-0.283	-0.288	-0.296
72	ECE	-0.311	-0.312	-0.315	-0.315	-0.315	-0.316
73	Controls	-0.275	-0.277	-0.273	-0.270	-0.274	-0.273
74	Controls	-0.349	-0.349	-0.353	-0.352	-0.355	-0.359
75	EN + Calcium	-0.337	-0.249	-0.262	-0.221	-0.194	-0.191
76	EN + Calcium	-0.369	-0.361	-0.383	-0.375	-0.390	-0.396
77	ECE	-0.300	-0.303	-0.313	-0.307	-0.311	-0.317
78	ECE	-0.290	-0.289	-0.257	-0.239	-0.222	-0.205

Table 6. Corrosion Potentials for Specimens 29-40, 67-78 (Continued)

Specimen #	6/27/2008	7/2/2008	7/8/2008	7/9/2008	7/10/2008	7/11/2008	7/14/2008	7/15/2008
29	-0.405	-0.358	-	-0.292	-	-	-	-
30	-0.098	-0.092	-	-0.075	-	-	-	-
31	-0.386	-0.452	-0.914	-0.949	-0.959	-0.896	-0.873	-0.903
32	-0.327	-0.339	-0.957	-0.984	-1.007	-0.952	-0.932	-
33	-0.249	-0.204	-1.012	-0.941	-1.028	-0.955	-0.919	-0.905
34	-0.334	-0.344	-1.059	-1.139	-1.085	-1.004	-0.910	-
35	-0.060	-0.108	-	-0.171	-	-	-	-
36	-0.323	-0.337	-	-0.272	-	-	-	-
37	-0.266	-0.272	-0.954	-1.017	-0.984	-0.917	-0.932	-
38	-0.333	-0.326	-0.924	-1.095	-1.058	-0.954	-0.956	-
39	-0.239	-0.250	-1.046	-1.046	-1.087	-1.007	-0.946	-
40	-0.272	-0.309	-0.847	-1.151	-1.097	-0.980	-0.727	-
67	-0.359	-0.373	-	-0.144	-	-	-	-
68	-0.270	-0.275	-	-0.106	-	-	-	-
69	-0.231	-0.223	-0.952	-1.064	-0.980	-0.910	-0.926	-
70	-0.234	-0.232	-	-0.180	-	-	-	-0.954
71	-0.284	-0.300	-1.041	-1.055	-1.176	-1.057	-0.979	-
72	-0.302	-0.314	-	-0.253	-	-	-	-0.989
73	-0.257	-0.273	-	-0.268	-	-	-	-
74	-0.359	-0.398	-	-0.281	-	-	-	-
75	-0.226	-0.272	-0.938	-0.985	-0.996	-0.944	-0.929	-
76	-0.382	-0.391	-	-0.256	-	-	-	-1.014
77	-0.306	-0.326	-1.013	-1.081	-1.050	-0.957	-0.900	-
78	-0.177	-0.142	-	-0.115	-	-	-	-1.028

Table 6. Corrosion Potentials for Specimens 29-40, 67-78 (Continued)

Specimen #	7/16/2008	7/17/2008	7/18/2008	7/21/2008	7/23/2008
29	-0.189	-	-	-	-0.230
30	-0.241	-	-	-	-0.250
31	-0.912	-	-	-	-0.752
32	-0.766	-	-	-	-0.703
33	-0.872	-	-	-	-0.098
34	-0.835	-	-	-	-0.074
35	-0.208	-	-	-	-0.255
36	-0.321	-	-	-	-0.322
37	-0.793	-	-	-	-0.743
38	-0.821	-	-	-	-0.725
39	-0.850	-	-	-	-0.809
40	-0.830	-	-	-	-0.795
67	-0.165	-	-	-	-0.237
68	-0.195	-	-	-	-0.130
69	0.206	-	-	-	-0.342
70	-0.987	-0.974	-0.919	-0.850	-0.774
71	-0.844	-	-	-	-0.798
72	-0.939	-0.997	-0.921	-0.896	-0.841
73	-0.296	-	-	-	-0.331
74	-0.273	-	-	-	-0.301
75	-0.791	-	-	-	-0.530
76	-0.956	-0.981	-0.913	-0.887	-0.790
77	-0.841	-	-	-	-0.069
78	-1.026	-1.073	-1.008	-0.964	-0.847

All potentials reported with reference to S.H.E. and in units of volts.

A.3 Corrosion Potentials for Atmospheric Specimens

Table 7. Corrosion Potentials for Specimens 29-40, 67-78

Specimen #	Treatment Type	6/19/2008	6/20/2008	6/23/2008	6/24/2008	6/25/2008	6/26/2008
41	Controls	-0.283	-0.285	-0.286	-0.258	-0.280	-0.280
42	Controls	-0.233	-0.236	-0.217	-0.206	-0.196	-0.216
43	Controls	-0.385	-0.388	-0.389	-0.386	-0.387	-0.387
44	EN	-0.276	-0.276	-0.268	-0.256	-0.302	-0.301
45	EN	-0.263	-0.267	-0.272	-0.265	-0.263	-0.264
46	EN	-0.269	-0.273	-0.276	-0.271	-0.271	-0.272
47	ECE	-0.306	-0.313	-0.319	-0.313	-0.321	-0.326
48	ECE	-0.268	-0.267	-0.263	-0.264	-0.253	-0.256
49	ECE	-0.245	-0.245	-0.237	-0.228	-0.228	-0.226
50	Controls	-0.314	-0.317	-0.322	-0.320	-0.317	-0.319
51	Controls	-0.236	-0.238	-0.243	-0.242	-0.245	-0.249
52	Controls	-0.320	-0.321	-0.323	-0.314	-0.310	-0.300
53	EN + Calcium	-0.257	-0.261	-0.266	-0.255	-0.249	-0.249
54	EN + Calcium	-0.134	-0.138	-0.160	-0.147	-0.139	-0.141
55	EN + Calcium	-0.209	-0.209	-0.217	-0.211	-0.209	-0.211
56	ECE	-0.375	-0.386	-0.405	-0.399	-0.387	-0.383
57	ECE	-0.303	-0.305	-0.302	-0.296	-0.295	-0.292
58	ECE	-0.221	-0.220	-0.213	-0.214	-0.216	-0.223
79	Controls	-0.339	-0.344	-0.356	-0.353	-0.359	-0.362
80	Controls	-0.392	-0.397	-0.401	-0.402	-0.408	-0.408
81	EN	-0.399	-0.392	-0.321	-0.310	-0.309	-0.306
82	EN	-0.196	-0.193	-0.200	-0.203	-0.208	-0.216
83	ECE	-0.261	-0.261	-0.262	-0.262	-0.271	-0.269
84	ECE	-0.263	-0.264	-0.265	-0.264	-0.273	-0.272
85	Controls	-0.301	-0.302	-0.300	-0.296	-0.300	-0.299
86	Controls	-0.264	-0.251	-0.261	-0.250	-0.274	-0.293
87	EN + Calcium	-0.337	-0.344	-0.351	-0.348	-0.348	-0.332
88	EN + Calcium	-0.276	-0.273	-0.271	-0.266	-0.260	-0.260
89	ECE	-0.264	-0.262	-0.265	-0.282	-0.289	-0.291
90	ECE	-0.283	-0.279	-0.264	-0.253	-0.257	-0.237
91	Controls	-0.176	-0.168	-0.177	-0.209	-0.159	-0.207
92	Controls	-0.299	-0.302	-0.313	-0.314	-0.321	-0.319

Table 7. Corrosion Potentials for Specimens 29-40, 67-78 (Continued)

Specimen #	6/27/2008	7/2/2008	7/10/2008	7/15/2008	7/16/2008	7/17/2008	7/18/2008	7/21/2008
41	-0.266	-0.263	-0.175	-	-	-0.272	-	-
42	-0.204	-0.217	-0.211	-	-	-0.273	-	-
43	-0.373	-0.348	-0.241	-	-	-0.263	-	-
44	-0.281	-0.281	-0.265	-0.947	-0.934	-0.911	-0.920	-0.838
45	-0.246	-0.257	-0.235	-	-	-0.339	-	-
46	-0.255	-0.256	-0.214	-	-	-0.273	-	-
47	-0.313	-0.334	-0.289	-0.929	-0.919	-0.979	-0.921	-0.871
48	-0.239	-0.245	-0.222	-	-	-0.236	-	-
49	-0.211	-0.214	-0.193	-	-	-0.245	-	-
50	-0.307	-0.312	-0.138	-	-	-0.232	-	-
51	-0.238	-0.254	-0.203	-	-	-0.213	-	-
52	-0.281	-0.255	-0.265	-	-	-0.291	-	-
53	-0.233	-0.232	-0.241	-0.924	-1.032	-0.987	-0.908	-0.928
54	-0.127	-0.139	-0.139	-0.940	-1.040	-0.969	-0.977	-0.927
55	-0.197	-0.215	-0.220	-	-	-0.309	-	-
56	-0.359	-0.320	-0.147	-1.042	-0.974	-0.987	-0.965	-0.939
57	-0.275	-0.283	-0.282	-1.041	-1.062	-1.128	-0.950	-0.982
58	-0.208	-0.221	-0.184	-	-	-0.185	-	-
79	-0.347	-0.367	-0.248	-	-	-0.270	-	-
80	-0.394	-0.410	-0.129	-	-	-0.104	-	-
81	-0.290	-0.313	-0.158	-	-	-0.164	-	-
82	-0.232	-0.302	-0.277	-	-	-0.207	-	-
83	-0.253	-0.269	-0.222	-	-	-0.315	-	-
84	-0.261	-0.304	-0.257	-	-	-0.256	-	-
85	-0.283	-0.294	-0.080	-	-	-0.208	-	-
86	-0.286	-0.320	-0.074	-	-	-0.276	-	-
87	-0.358	-0.361	-0.244	-	-	-0.285	-	-
88	-0.245	-0.327	-0.299	-	-	-0.313	-	-
89	-0.274	-0.274	-0.201	-	-	-0.247	-	-
90	-0.234	-0.289	-0.306	-	-	-0.333	-	-
91	-0.179	-0.240	-0.278	-	-	0.316	-	-
92	-0.303	-0.303	-0.252	-	-	0.316	-	-

Table 7. Corrosion Potentials for Specimens 29-40, 67-78 (Continued)

Specimen #	7/22/2008	7/23/2008	7/24/2008	7/25/2008
41	-	-	-0.301	-
42	-	-	-0.259	-
43	-	-	-0.257	-
44	-	-	-0.742	-
45	-0.870	-0.900	-0.917	-0.905
46	-0.847	-0.890	-0.924	-0.886
47	-	-	-0.148	-
48	-0.949	-0.987	-1.002	-0.951
49	-0.925	-0.985	-1.011	-0.954
50	-	-	-0.262	-
51	-	-	-0.210	-
52	-	-	-0.304	-
53	-	-	-0.736	-
54	-	-	-0.761	-
55	-0.898	-0.911	-0.922	-0.907
56	-	-	-0.825	-
57	-	-	-0.831	-
58	-0.949	-0.986	-1.008	-0.947
79	-	-	-0.251	-
80	-	-	-0.117	-
81	-0.904	-0.898	-0.910	-0.892
82	-0.875	-0.905	-0.909	-0.896
83	-0.924	-0.985	-1.014	-0.972
84	-0.919	-0.986	-1.013	-0.966
85	-	-	-0.241	-
86	-	-	-0.241	-
87	-0.935	-0.893	-0.898	-0.891
88	-1.000	-0.911	-0.937	-0.940
89	-0.940	-0.988	-1.002	-0.932
90	-0.983	-0.989	-1.005	-0.934
91	-	-	-0.312	-
92	-	-	-0.233	-

All potentials reported with reference to S.H.E. and in units of volts.

APPENDIX B. CORROSION RATE MEASUREMENTS

B.1 Corrosion Rates for Controls and Specimens Treated First Week

Table 8. Corrosion Rate for Controls

Specimen	Type of treatment	6/23/2008	7/28/2008
1	Controls	0.30	-
2	Controls	0.11	-
3	Controls	0.48	-
4	Controls	0.72	-
5	Controls	0.58	1.45
6	Controls	0.64	6.61
7	Controls	0.49	-
8	Controls	0.27	69.0 / 2.60
9	Controls	0.29	5.22
10	Controls	0.26	5.96
11	Controls	0.12	34.45 / 8.74
12	Controls	0.27	-
13	Controls	0.11	-
15	Controls	0.98	0.65
16	Controls	0.30	0.50
17	Controls	0.19	0.59
18	Controls	0.62	0.40

Table 9. Corrosion Rate for Specimens Treated During First Week

Specimen	Type of treatment	6/24/2008	6/25/2008	6/27/2008	6/30/2008	7/28/2008
19	EN, Calcium	6.28	0.61	2.18	0.25	-
20	EN, Calcium	0.42	0.32	0.10	0.21	1.18
21	EN, Calcium	0.26	0.12	0.21	1.97	1.97
22	EN	10.61 / 2.19 ²	4.36 / 2.04	0.36	2.00	-
23	EN	4.35	0.24	0.24	-	-
24	ECE	7.21	3.92	5.73	5.60	-
25	ECE	7.15 / 2.51	7.90	7.49 / 2.67	6.32	-
26	ECE	9.62 / 2.77	4.95 / 2.25	7.05 / 1.86	8.68	-
27	ECE	1.01	1.54	0.40	0.67	-
28	ECE	8.92	5.59	6.95	-	-
65	EN	1.37	0.86	0.34	1.71	24.01 / 3.14
66	ECE	0.59	0.48	0.24	2.87	-

Notes:

1. All corrosion rates reported with units of mpy.
2. Two values reported because of uncertainty of polarization resistance graph; these values were disregarded when average corrosion rates were calculated.

B.2 Corrosion Rates for Specimens Treated Second Week and Third Week**Table 10. Corrosion Rate for Specimens Treated During Second Week**

Specimen	Type of treatment	7/1/2008	7/3/2008	7/7/2008	7/28/2008
5	EN, Calcium	0.15	0.24	0.69	-
6	EN, Calcium	0.72	0.51	1.32	-
7	EN, Calcium	0.89	0.07	3.18 / 1.66	-
8	EN	0.13	0.34	2.07	-
9	EN	0.31	0.42	2.67	-
10	ECE	0.33	0.59	1.38	-
11	ECE	2.88 / 2.03	2.93	1.27	-
12	ECE	0.49	0.19	2.90	-
13	ECE	0.63	0.67	2.96	19.75 / 3.67
14	ECE	-	1.06	3.11	17.10 / 3.86
61	EN	1.11	1.14	3.67	3.87
62	ECE	0.81	2.73 / 2.32	2.30 / 1.93	-

Table 11. Corrosion Rate for Specimens Treated During Third Week

Specimen	Type of treatment	7/8/2008	7/11/2008	7/14/2008	7/15/2008	7/16/2008
31	EN	2.90 / 1.72 ²	0.67	3.19	1.83	2.86
32	EN	0.98	0.51	1.25	-	-
33	ECE	1.64	0.96	6.18	9.11	8.44
34	ECE	-	0.34	1.83	-	-
37	EN, Calcium	3.75 / 1.48	1.47	1.31	-	-
38	EN, Calcium	3.55	0.35	1.16	-	-
39	ECE	0.38	0.11	0.26	-	-
40	ECE	1.19	0.11	1.00	-	-
69	EN	0.96	0.65	1.12	-	-
71	ECE	0.29	0.23	-	-	-
75	EN, Calcium	13.19 / 3.62	0.24	0.61	-	-
77	ECE	9.03 / 2.66	0.54	6.80	-	-

Notes:

1. All corrosion rates reported with units of mpy.
2. Two values reported because of uncertainty of polarization resistance graph; these values were disregarded when average corrosion rates were calculated.

B.3 Corrosion Rates for Specimens Treated Fourth Week and Fifth Week**Table 12. Corrosion Rates for Specimens Treated During Fourth Week**

Specimen	Type of treatment	7/15/2008	7/18/2008	7/21/2008
44	EN	5.32 / 1.38	1.37	2.66
47	ECE	6.67 / 2.03	9.40	8.62
53	EN, Calcium	6.28 / 1.46	0.92	0.89
54	EN, Calcium	5.80 / 1.72	0.60	1.19
56	ECE	0.25	0.95	8.09
57	ECE	1.48	0.60	4.37
70	EN	4.89 / 1.42	0.81	0.80
72	ECE	2.19	10.59	9.60
76	EN, Calcium	0.47	0.37	5.68
78	ECE	5.25 / 1.74	2.13	4.10

Table 13. Corrosion Rates for Specimens Treated During Fifth Week

Specimen	Type of treatment	7/22/2008	7/25/2008	7/28/2008
45	EN	6.67 / 2.06	2.77	2.92
46	EN	8.17 / 1.48	4.48	2.54
48	ECE	9.88 / 2.32	2.11	0.64
49	ECE	7.78 / 1.89	1.14	0.43
55	EN, Calcium	6.55 / 2.00	2.65	1.08
58	ECE	11.14 / 2.15	1.36	0.28
81	EN	8.72	2.54	2.56
82	EN	5.96 / 2.16	3.29	3.05
83	ECE	10.55 / 2.82	0.47	1.98
84	ECE	7.06 / 1.97	0.63	0.59
87	EN, Calcium	3.22	1.40	0.42
88	EN, Calcium	7.37 / 1.58	1.03	1.41
89	ECE	8.90 / 1.91	1.97	0.58
90	ECE	5.40 / 1.90	3.37	2.02

Notes:

1. All corrosion rates reported with units of mpy.
2. Two values reported because of uncertainty of polarization resistance graph; these values were disregarded when average corrosion rates were calculated.

APPENDIX C. VOLTAGE AND CURRENT DURING TREATMENT

C.1 Voltage / Current During First Week of Treatment

Table 14. Voltage / Current During First Week of Treatment

Specimen	Treatment	6/23/2008		6/24/2008			
		Voltage Drop	Current	Before adjustment		After adjustment	
				Voltage Drop	Current	Voltage Drop	Current
19	EN, Calcium	37.3	200	33.4	110	36.6	170
24	ECE	14.6	200	18.6	110	15.1	170
20	EN, Calcium	37.4	170	-	-	37.4	120
25	ECE	22.7	170	-	-	17	120
21	EN, Calcium	35.9	140	41.3	130	37.5	120
26	ECE	31.7	140	26.5	130	20.7	120
22	EN	26.5	130	19.8	110	22.6	120
27	ECE	33.2	130	39.8	110	37.3	120
23	EN	37.5	200	46.2	200	35.8	190
28	ECE	18.9	200	16.8	200	15.2	190
65	EN	32.7	150	28.7	100	31.2	130
66	ECE	36	150	39.9	100	40.5	130

Table 14. Voltage / Current During First Week of Treatment (Continued)

Specimen	6/25/2008				6/26/2008	
	Before adjustment		After adjustment		Before adjustment	
	Voltage Drop	Current	Voltage Drop	Current	Voltage Drop	Current
19	36.9	70	37.4	110	36.7	50
24	17.7	70	14.7	110	15.4	50
20	37.3	60	37.5	130	38.8	50
25	17.4	60	14.9	130	14.9	50
21	40.1	50	37.4	100	37.9	60
26	17.8	50	17.4	100	16.5	60
22	18.4	70	37.2	120	37.2	80
27	42.1	70	47.3	120	49.6	80
23	45.6	70	37.1	90	38.6	60
28	7.2	70	7.5	90	5.7	60
65	31.4	70	37.3	60	38.3	50
66	41.2	70	42.8	60	42.9	50

Table 14. Voltage / Current During First Week of Treatment (Continued)

Specimen	6/26/2008		6/27/2008			
	After adjustment		Before adjustment		After adjustment	
	Voltage Drop	Current	Voltage Drop	Current	Voltage Drop	Current
19	37.3	60	37.4	50	37.4	30
24	16.4	60	15.8	50	8.6	30
20	37.3	50	38.2	40	37.1	95
25	13.7	50	13.5	40	15.8	95
21	37.2	40	37.9	40	37.2	86
26	15.8	40	15.8	40	14.0	86
22	-	-	38.2	40	37.3	95
27	-	-	47.0	40	45.4	95
23	37.1	20	37.1	40	37.4	100
28	4.4	20	4.5	40	6.3	100
65	37.3	40	40.1	40	37.4	90
66	40.3	40	40.2	40	40.4	90

Table 14. Voltage / Current During First Week of Treatment (Continued)

Specimen	6/30/2008	
	Voltage Drop	Current
19	39.2	40
24	6.5	40
20	40.2	40
25	13.1	40
21	41.4	32
26	11.6	32
22	36.7	60
27	46.2	60
23	42.8	30
28	22.7	30
65	37.7	60
66	40.6	60

All voltage drops have units of volts and currents have units of milliamps.

C.2 Voltage / Current During Second Week of Treatment

Table 15. Voltage / Current During Second Week of Treatment

Specimen	Treatment	6/30/2008		7/1/2008			
		Voltage Drop	Current	Before adjustment		After adjustment	
				Voltage Drop	Current	Voltage Drop	Current
5	EN, Calcium	37.4	410	36.7	90	37.1	120
10	ECE	32.8	410	33.1	90	28.9	120
6	EN, Calcium	35.2	130	41.5	110	37.3	120
11	ECE	34.9	130	29.2	110	26.5	120
7	EN, Calcium	37.5	170	35.5	100	37.5	120
12	ECE	37.9	170	42.7	100	43.3	120
8	EN	28	360	38.5	95	37.3	130
14	ECE	56.8	360	46.4	95	49.9	130
9	EN	36.6	160	38.2	90	37.2	120
13	ECE	38.3	160	37.4	90	34.9	120
61	EN	37.1	140	32	95	37.1	130
62	ECE	28.9	140	34.2	95	34.4	130

Table 15. Voltage / Current During Second Week of Treatment (Continued)

Specimen	7/2/2008				7/3/2008	
	Before adjustment		After adjustment		Before adjustment	
	Voltage Drop	Current	Voltage Drop	Current	Voltage Drop	Current
5	31.6	50	37.3	90	32.5	140
10	32.9	50	37.8	90	30.1	140
6	40.7	50	37.1	30	34.2	50
11	22.7	50	21.8	30	24.2	50
7	41.1	80	37.2	70	40.5	60
12	42.3	80	40.3	70	40.3	60
8	41.8	180	37.3	130	42.3	150
14	45.4	180	42.5	130	40.4	150
9	40.8	50	37.2	40	38.7	50
13	64.5	50	33.2	40	30.8	50
61	38.4	60	37.3	50	40.2	60
62	31.5	60	30.2	50	26.8	60

Table 15. Voltage / Current During Second Week of Treatment (Continued)

Specimen	7/3/2008		7/7/2008	
	After adjustment		Voltage Drop	Current
	Voltage Drop	Current		
5	37.2	150	33.9	50
10	25.7	150	28.8	50
6	37.4	110	26.1	40
11	23.3	110	35.3	40
7	37	70	33.3	30
12	31.4	70	36.3	30
8	37.4	130	42.6	120
14	32.9	130	29.5	120
9	37.3	110	37.2	40
13	30.3	110	30.7	40
61	37.2	120	39.3	40
62	20.4	120	17.5	40

All voltage drops have units of volts and currents have units of milliamps.

C.3 Voltage / Current During Third Week of Treatment

Table 16. Voltage / Current During Third Week of Treatment

Specimen	Treatment	7/7/2008		7/8/2008			
		Voltage Drop	Current	Before adjustment		After adjustment	
				Voltage Drop	Current	Voltage Drop	Current
31	EN	37.5	150	29.7	130	37.5	180
33	ECE	19.1	150	26.8	130	21.8	180
32	EN	36.7	260	38.3	190	37.2	190
34	ECE	36.9	260	36.3	190	35.8	190
69	EN	37.5	170	40.3	100	37.3	130
71	ECE	48	170	47.3	100	42	130
37	EN, Calcium	37.5	150	32.7	110	37	150
39	ECE	36.8	150	42	110	38.7	150
38	EN, Calcium	37.5	280	38.2	160	37.5	200
40	ECE	37.6	280	37.8	160	37	200
75	EN, Calcium	37.5	320	37.2	310	37.4	410
77	ECE	34.4	320	33.3	310	37.3	410

Table 16. Voltage / Current During Third Week of Treatment (Continued)

Specimen	7/9/2008				7/10/2008	
	Before adjustment		After adjustment		Before adjustment	
	Voltage Drop	Current	Voltage Drop	Current	Voltage Drop	Current
31	34.3	60	37.4	70	38.5	50
33	26.8	60	27.1	70	28.2	50
32	41.7	120	37.1	80	37.4	90
34	32.8	120	31.4	80	30.1	90
69	39.2	80	37.3	60	38.3	40
71	42	80	40.8	60	40.2	40
37	33.5	50	36.4	50	40.1	70
39	41.5	50	40.1	50	40.3	70
38	39.6	140	37.3	120	39.3	90
40	37.2	140	35.8	120	36.4	90
75	38.9	110	37.4	90	38.9	70
77	36.9	110	34.1	90	32.1	70

Table 16. Voltage / Current During Third Week of Treatment (Continued)

Specimen	7/10/2008		7/11/2008			
	After adjustment		Before adjustment		After adjustment	
	Voltage Drop	Current	Voltage Drop	Current	Voltage Drop	Current
31	37.3	50	41.4	40	37.4	100
33	29.7	50	24.4	40	23	100
32	-	-	37.4	70	37.5	130
34	-	-	30.2	70	27.5	130
69	37	40	37.8	40	37.3	80
71	39.7	40	40.7	40	38.2	80
37	37.2	50	37	50	37.2	90
39	39.9	50	42.7	50	36.6	90
38	37.3	70	40.2	70	37.4	120
40	35.2	70	35.6	70	30.3	120
75	37.3	40	40.1	60	37.4	60
77	28.8	40	28.1	60	22.7	60

Table 16. Voltage / Current During Third Week of Treatment (Continued)

Specimen	7/14/2008			
	Before adjustment		After adjustment	
	Voltage Drop	Current	Voltage Drop	Current
31	37.5	230	37.5	200
33	15.2	230	13.3	200
32	36.3	70	-	-
34	29.3	70	-	-
69	36.7	80	-	-
71	38.9	80	-	-
37	34.4	50	-	-
39	37.4	50	-	-
38	37.1	50	-	-
40	33.1	50	-	-
75	38.2	50	-	-
77	21.1	50	-	-

Table 16. Voltage / Current During Third Week of Treatment (Continued)

Specimen	7/15/2008				7/16/2008	
	Before adjustment		After adjustment			
	Voltage Drop	Current	Voltage Drop	Current	Voltage Drop	Current
31	40.3	60	37.3	120	39.6	40
33	13.9	60	9.5	120	8.3	40

All voltage drops have units of volts and currents have units of milliamps.

C.4 Voltage / Current During Fourth Week of Treatment

Table 17. Voltage / Current During Fourth Week of Treatment

Specimen	Treatment	7/14/2008		7/15/2008			
		Voltage Drop	Current	Before adjustment		After adjustment	
				Voltage Drop	Current	Voltage Drop	Current
44	EN	37.5	110	46.5	140	37.3	110
47	ECE	28.4	110	19.6	140	15.8	110
70	EN	37.5	120	37.1	110	37.5	130
72	ECE	19.6	120	22.1	110	14.6	130
76	EN, Calcium	33	410	43	160	37.4	80
56	ECE	49.3	410	40.6	160	29.4	80
54	EN, Calcium	37.4	120	34.3	110	37.4	120
57	ECE	34.2	120	38.6	110	36.8	120
53	EN, Calcium	37.5	100	37	110	37.3	100
78	ECE	37	100	28.5	110	25	100

Table 17. Voltage / Current During Fourth Week of Treatment (Continued)

Specimen	7/16/2008				7/17/2008	
	Before adjustment		After adjustment		Before adjustment	
	Voltage Drop	Current	Voltage Drop	Current	Voltage Drop	Current
44	44.9	60	37.4	40	36.5	50
47	10.1	60	7.1	40	22.4	50
70	37.8	60	37.3	60	35.5	50
72	17.3	60	16.7	60	38.2	50
76	37.5	70	-	-	41.2	80
56	28.6	70	-	-	22	80
54	35.6	50	37.4	70	40.4	40
57	40.2	50	45.3	70	12.9	40
53	39.6	60	37.3	50	40.7	40
78	22.9	60	20.8	50	6.3	40

Table 17. Voltage / Current During Fourth Week of Treatment (Continued)

Specimen	7/17/2008		7/18/2008			
	After adjustment		Before adjustment		After adjustment	
	Voltage Drop	Current	Voltage Drop	Current	Voltage Drop	Current
44	37.2	70	40.1	40	37.2	80
47	8.7	70	60.2	40	9.5	80
70	37	80	40.2	40	37.4	100
72	9.4	80	7.3	40	9.3	100
76	37.5	130	41.6	60	37.2	190
56	19.2	130	20.2	60	15.7	190
54	37.4	100	34.3	40	37.3	110
57	34.7	100	37.7	40	35.7	110
53	37.2	90	37.3	40	37.4	80
78	20.8	90	20.9	40	18.7	80

Table 17. Voltage / Current During Fourth Week of Treatment (Continued)

Specimen	7/21/2008	
	Voltage Drop	Current
44	36.2	50
47	10.3	50
70	43	40
72	5.5	40
76	28.3	30
56	25.8	30
54	37.4	30
57	38.8	30
53	36.1	30
78	20.8	30

All voltage drops have units of volts and currents have units of milliamps.

C.5 Voltage / Current During Fifth Week of Treatment

Table 18. Voltage / Current During Fifth Week of Treatment

Specimen	Treatment	7/21/2008		7/22/2008			
		Voltage Drop	Current	Before adjustment		After adjustment	
				Voltage Drop	Current	Voltage Drop	Current
88	EN, Calcium	37.4	40	36.4	140	37.5	70
87	EN, Calcium	37.4	110	36.4	220	37.5	200
55	EN, Calcium	37.4	30	36.4	130	37.5	60
45	EN	37.4	50	36.4	160	37.5	80
46	EN	37.4	30	36.4	130	37.5	50
81	EN	37.4	120	36.4	250	37.5	170
82	EN	37.4	50	36.4	170	37.5	80
90	ECE	37.4	130	38.1	150	37.5	190
89	ECE	37.4	120	38.1	190	37.5	180
48	ECE	37.4	130	38.1	150	37.5	180
58	ECE	37.4	130	38.1	160	37.5	190
49	ECE	37.4	120	38.1	170	37.5	170
84	ECE	37.4	110	38.1	140	37.5	160
83	ECE	37.4	130	38.1	150	37.5	190

Table 18. Voltage / Current During Fifth Week of Treatment (Continued)

Specimen	7/23/2008				7/24/2008	
	Before adjustment		After adjustment		Before adjustment	
	Voltage Drop	Current	Voltage Drop	Current	Voltage Drop	Current
88	37.5	66	37.3	68	37.9	50
87	37.5	112	37.3	84	37.9	50
55	37.5	68	37.3	54	37.9	40
45	37.5	72	37.3	66	37.9	40
46	37.5	79	37.3	54	37.9	50
81	37.5	30	37.3	73	37.9	70
82	37.5	68	37.3	66	37.9	30
90	37.3	60	-	-	37.3	45
89	37.3	60	-	-	37.3	37
48	37.3	50	-	-	37.3	36
58	37.3	80	-	-	37.3	53
49	37.3	61	-	-	37.3	42
84	37.3	64	-	-	37.3	46
83	37.3	53	-	-	37.3	55

Table 18. Voltage / Current During Fifth Week of Treatment (Continued)

Specimen	7/24/2008		7/25/2008			
	After adjustment		Before adjustment		After adjustment	
	Voltage Drop	Current	Voltage Drop	Current	Voltage Drop	Current
88	37.4	50	37.2	33	37.5	95
87	37.4	60	37.2	54	37.5	230
55	37.4	40	37.2	35	37.5	95
45	37.4	40	37.2	34	37.4	72
46	37.4	40	37.2	37	37.4	76
81	37.4	60	37.2	68	37.4	84
82	37.4	40	37.2	30	37.4	81
90	-	-	37.2	46	37.4	120
89	-	-	37.2	59	37.4	80
48	-	-	37.2	44	37.4	100
58	-	-	37.2	46	37.4	110
49	-	-	37.2	34	37.4	100
84	-	-	37.2	30	37.4	100
83	-	-	37.2	36	37.4	140

Table 18. Voltage / Current During Fifth Week of Treatment (Continued)

Specimen	7/28/2008	
	Voltage Drop	Current
88	38.5	41
87	38.5	62
55	38.5	30
45	37.7	23
46	37.7	28
81	37.7	42
82	37.7	31
90	37.8	165
89	37.8	35
48	37.8	56
58	37.8	48
49	37.8	23
84	37.8	44
83	37.8	125

All voltage drops have units of volts and currents have units of milliamps.

APPENDIX D. CALIBRATION OF REFERENCE ELECTRODES

D.1 Calibration of Reference Electrodes

The reference potential between two similar reference electrodes was checked and recorded daily. This check was performed before any corrosion potential measurements were conducted.

Table 19. Potential Difference Between Similar Electrodes

Date	Reference Electrode		
	Ag / AgCl ₂	Cu / CuSO ₄	S.C.E.
6/19/2008	< 5	-	-
6/20/2008	< 5	-	-
6/23/2008	3.7	-	-
6/24/2008	3.5	-	-
6/27/2008	0.3	-	-
7/8/2008	-	0.8	-
7/9/2008	-	2.9	0.7
7/10/2008	-	2.0	0.8
7/11/2008	-	2.8	-
7/14/2008	0.9	2.5	-
7/15/2008	-	1.1	-
7/16/2008	-	0.1	0.9
7/17/2008	-	1.6	0.9
7/18/2008	-	< 1	-
7/21/2008	-	< 1	-
7/22/2008	-	1.2	-
7/23/2008	-	2.0	-
7/24/2008	-	1.1	-
7/25/2008	-	0.9	-
7/28/2008	-	1.3	-
7/29/2008	-	1.0	-
8/8/2008	-	0.2	-

All potentials have units of millivolts.

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