

**"The Evaluation of Corrosion Inhibitors
for the Repair and Rehabilitation of
Reinforced Concrete Bridge Components"**

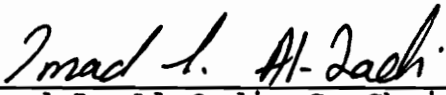
by

Brian D. Prowell

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APPROVED:


Richard E. Weyers, Chairman


Imad L. Al-Qadi, Co-Chairman


Richard M. Barker

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The Evaluation of Corrosion Inhibitors
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Committee Chairman: Richard E. Weyers
Civil Engineering

(Abstract)

In 1991, seven corrosion inhibitors, surface applied liquids and concrete admixtures, were identified as promising for the repair of reinforced concrete structures subject to chloride induced corrosion.

Small scale (1 ft.²) reinforced concrete specimens were cast to evaluate the inhibitors effectiveness. A treatment matrix was established to evaluate the inhibitors performance on three ranges of corrosion activity and evaluate the effect of application time and drying. Corrosion rate measurements taken with a linear polarization device were used to monitor the inhibitors effectiveness.

The effect of the admixtures on the concrete properties, and the effect of the surface applied inhibitors on the overlay bond strength were evaluated. Rapid freeze-thaw tests were conducted to estimate the durability of the inhibitor modified concrete.

Three combinations of inhibitors were identified for large scale testing after ten months of accelerated chloride

exposure. The larger specimens, removed from an actual bridge deck, were treated to test the effective inhibitors field application techniques.

Service life estimates were made for the two combinations of inhibitors which were most effective to aid the engineer in assessing the inhibitors cost effectiveness.

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1.0 Introduction

1.1 Description of Problem

Bridges are an integral part of our transportation infrastructure. Removing one of these structures from the highway network forces the transportation public to use alternate routes, an economic cost measured in time and money. In some cases, no alternate route exists. A recent U.S. Department of Transportation report stated that, 39% of the 576,665 bridges on the nation's federal aid highway system are structurally deficient or functionally obsolete [1]. Approximately, 40% of the deficient bridges are related to chloride induced corrosion of the reinforcement steel within the structures reinforced concrete components [2]. Considering the important role bridges play in our transportation system, and the number of these structures which are in need of repair or replacement, it is important to identify ways to mitigate the corrosion problem in an economically efficient manner.

Reinforced concrete is the most prominent building material used in transportation structures. A primary source of deterioration in reinforced concrete structures, especially in the northern climates and coastal regions, is chloride induced corrosion of the reinforcement steel. The primary source of chlorides in the northern climates is deicing salts, while in marine environments it is sea spray.

In as little as 5 years of exposure, damage may occur in marine environments [3].

Prior to critical chloride contamination, estimated to be at or above 1.2 lbs/yd³, the pH of the concrete (greater than 12.5) is usually sufficiently high to prevent the corrosion of unprotected reinforcement steel [4]. The ingress of chlorides disrupts the protective layer of ferric oxide on the reinforcement steel, and lowers both the resistivity and the pH of the concrete. These changes, along with sufficient moisture and free oxygen create a spontaneous corrosion environment.

Corrosion of the reinforcement steel results in cracking, delamination, and spalling of the concrete cover. The damage is not normally sufficient to reduce the structures load bearing capacity [5]. However, on bridge decks the damage reduces the rideability of the surface, which creates unsafe travel conditions.

Bridge decks are typically rehabilitated when 30 to 40 percent of the riding surface is damaged. The damage is the total area sum of delaminations and spalls [6].

1.2 Current Repair Techniques

Currently, there are several accepted methods used in the prevention, repair, and rehabilitation of deteriorated concrete bridge components as a result of chloride induced corrosion. The application of these treatments is presented

in Figure 1. The mechanism of protection provided by these methods lie in to one of three categories:

- (1) Methods which provide a protective coating for the reinforcement steel.
- (2) Methods which reduce the permeability of the concrete, thus reducing the rate of diffusion of chlorides and moisture.
- (3) Electrochemical Methods.

In new structures, protection may be afforded by treatment of the reinforcement steel prior to placing the concrete.

The use of epoxy coated rebar has been wide spread in recent construction. The best coating is provided by a thermal cure of applied dry powdered epoxy. The reliability of the coating is debatable as it may be damaged in shipping and handling. The epoxy coating prevents chlorides from contacting the reinforcement steel and acts as a dielectric. Some construction employs coated steel for only the top mat of reinforcing. The dielectric nature of the coating prevents the electrical coupling of the mats, thus preventing macro-cell corrosion. However, a small imperfection can lead to accelerated corrosion due to the large cathodic area provided by the bottom mat [7].

Galvanized reinforcing steel, where the surface is coated with zinc by hot dipping, has also been used. Unlike epoxy coated rebar, the zinc produces a galvanic couple, and

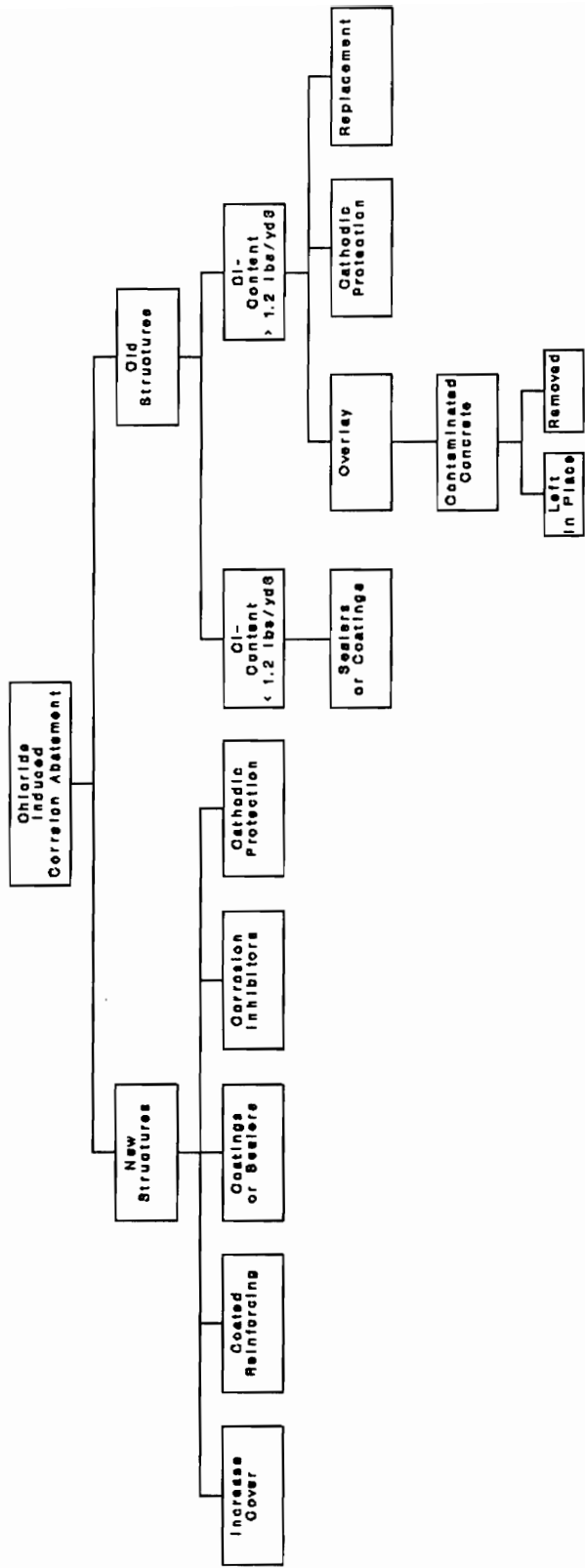


Figure 1. Current Prevention, Repair, and Rehabilitation Techniques

acts as a sacrificial anode. Therefore, the zinc protects the steel even if the coating is damaged.

On bridge decks and sub-structures where the concrete has not yet been critically contaminated with chlorides, coatings and sealers are often applied as a low initial cost method of reducing chloride ingress. Both coatings and sealers are subject to weathering and wear and periodical applications are necessary.

The most common rehabilitation techniques used on bridge decks are overlay systems. These include: normal concrete overlays, bituminous concrete overlays in conjunction with a membrane system, latex modified overlays, low slump dense concrete overlays, and thin polymer overlays. These overlay systems attempt to reduce the corrosion of the reinforcement steel by decreasing the ingress of chlorides and moisture.

Prior to overlay, the unsound concrete is normally removed to or below the bar level and the exposed rebar is sandblasted to near white metal. This process is extremely expensive and does not guarantee the removal of all of the corrosion products from the bar. The preparation described above does not address the areas where the corrosion has not advanced to a state where the concrete has cracked or delaminated, even though these areas may be chloride contaminated. If this is the case, then the corrosion process may continue, assuming the necessary moisture and

free oxygen are available. Thus, the anticipated increase in service life using these rehabilitation techniques may be significantly shortened because the steel continues to corrode in the chloride contaminated areas.

Two electrochemical methods have been developed, cathodic protection and chloride migration. Cathodic protection supplies an external source of current to the reinforcing steel, reversing the corrosion reaction. The current is applied through an external anode added to the structure. The power requirements, approximately 0.015 watts/m² of concrete [8], are minimal and can be supplied by a solar panel. This method can only be applied to structures with electrically continuous reinforcing steel.

In the second experimental method, a D.C. potential is applied to the concrete which causes the chloride ions to migrate to a surface anode where they are captured by an electrolyte solution [9]. The methods use is hindered by the power requirements and application time. Additionally, the porosity of the concrete is increased as a result of the treatment.

1.3 Scope of Study

In a previous corrosion inhibitor feasibility study by Collins [10], four combinations of corrosion inhibitors were identified for further study. The current investigation proposes to develop procedures for the use of corrosion

inhibitors on bridge components for which the chloride contaminated concrete has been removed to at least the top layer of reinforcing steel. The study will evaluate the effectiveness of the inhibitors when applied in a manner practical for field construction, and determine the procedures which should be employed to ensure their successful application. The project was performed in three phases:

I) Evaluation of Corrosion Inhibitors

II) Development of Field Treatment Procedures

III) Estimation of Service Life

The first phase employed small scale laboratory specimens in which corrosion was accelerated by repeated chloride exposure. A treatment matrix was devised to test the effectiveness of the application procedures on varying rates of corrosion. The change in corrosion rate was measured by non-destructive techniques.

Those treatments which proved effective in Phase I were continued in Phase II, which determined the necessary application procedures for field use. Various parameters which would affect constructability were investigated. These include the effect of the inhibitors on the strength, workability, and durability of the modified concrete. Procedures were developed to minimize any detrimental effects where possible. This phase culminated in the treatment of sections removed from an actual bridge deck.

The final phase attempted to estimate the additional service life provided by the treatments.

2.0 Background

2.1 Concrete

Mehta states that "the present consumption of concrete in the world is of the order of 4.5 billion tons every year" [11]. This makes it the most widely used building material in the world.

Concrete is a composite material consisting of coarse to fine aggregate held together with a cementitious material or binder.

The term aggregate refers to the granular materials such as sand, gravel, crushed stone, or iron blast-furnace slag which make up the greatest percentage of the concrete composition. Particles larger than 4.75 mm (No. 4 sieve) are considered coarse aggregate. Particles smaller than 4.75 mm but larger than 75 μm (No. 200 sieve) are termed fine aggregate [12].

Portland cement is the most common form of hydraulic cement used in construction. The principal constituents of the hydrated portland cement paste are calcium silicate hydrate, calcium hydroxide, and calcium sulfo-aluminates. These compounds constitute 50 to 60, 20 to 25, and 15 to 20 percent respectively, of the total volume of the hydrated paste [11].

Blended hydraulic cements, which mix fine materials such as pozzalans or blast-furnace slag with portland

cement, are used to obtain specialized concrete mixes. Organic polymers, such as epoxy, are also used as binder mediums.

2.2 Corrosion

2.2.1 Overview

Corrosion is defined as "the deterioration of a substance (usually a metal) or its properties because of a reaction with its environment" [13]. There are two general categories of corrosion: dry and wet or aqueous. Dry corrosion occurs when a metal reacts with vapors at high temperatures. Wet corrosion is the primary form of deterioration. It typically occurs when a metal reacts with electrolytes in an aqueous environment [14].

The mechanism of deterioration is either chemical or electrochemical. The reaction which occurs when an acid attacks a metal would be termed chemical corrosion. R. P. Brown *et al* state that "an electrochemical reaction involves metals, chemicals and water that combine to form cells capable of generating electricity" [14]. The four basic components that make up an electrochemical cell are the anode, cathode, electrolyte, and conductor.

Oxidation occurs at the anode or positive electrode according to the following reaction:



where,

M \equiv a metal.

n = electron valence number.

The electrons produced in the oxidation reaction are carried by the conductor to the cathode where a reduction reaction takes place. Ions produced in the reactions are transferred by ionic conductance in the electrolyte solution. Faraday's Second Law states that the rate of reaction at the anode must equal that of the cathode in order to maintain electrochemical equilibrium.

There are three primary forms of electrochemical cells: galvanic, concentration and electrolytic. Galvanic cells result when two metals with different electromotive forces are coupled in the presence of an electrolyte. The zinc coating sometimes applied to reinforcing steel creates a galvanic cell where the zinc is the sacrificial anode in the presence of Cl⁻ ions.

The anode and cathode are the same material in a concentration cell. The electromotive force is provided by different concentrations of chemicals in the electrolyte solution [15].

All of the necessary components except a driving potential exist in an electrolytic cell. This is provided by an external source such as stray currents.

Corrosion is manifested in several forms, the most common are uniform and pitting. Uniform corrosion occurs over the entire exposed surface at a constant rate. Pitting corrosion is a localized form of corrosion initiated by a surface defect. The reaction is self-supporting with the oxidation reaction generally occurring in the pit while reduction occurs at the mouth of the pit [16]. Crevice corrosion is similar to pitting corrosion.

Intergranular corrosion can occur in certain alloys along the grain boundaries due to differences in chemical composition of the grains. The grains themselves are generally unaffected [14,16].

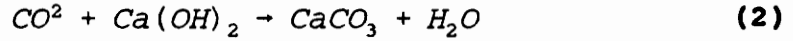
2.2.2 Corrosion of Steel in Concrete

One of the advantages of reinforced concrete construction is the passivity of the steel in the concrete environment. The pore water solution in concrete is at least as alkaline as saturated lime water ($\text{pH} = 12.4$) and the presence of small amounts of sodium and potassium oxides may increase the alkalinity to between 12.5 and 13.2 [17].

It is generally believed that the high pH (> 12) in the concrete causes a stable layer of ferric oxide (Fe_2O_3) to form on the surface of the steel [11]. Recent research indicates that this passive layer may actually be a protective mineral scale [18], however this theory will require further validation. Unfortunately, carbonation or

the presence of Cl^- ions can disrupt the steels passivity.

Carbonation occurs according to the following reaction:



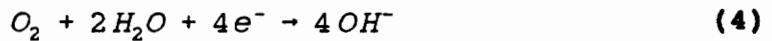
which lowers the pH of the concrete. This causes the layer of ferric oxide to become unstable allowing corrosion to occur. However, carbonation induced corrosion is not a significant problem in the United States. Low permeability cover concrete acts as a barrier against the ingress and a chemical absorber of carbon dioxide [17].

The application of deicing salts and exposure to marine environments cause chloride induced corrosion of reinforced concrete structures. The Cl^- ion disrupts the protective coating of ferric oxide allowing corrosion to occur in the presence of oxygen according to the following reactions:

Anode reaction:



Cathode reaction:



The pore water acts as the electrolyte and the reinforcing steel acts as the conductor to complete the cell.

Generally, the reaction occurs in the manner of a combination cell, with the anode and cathode areas being

determined by differing concentrations of O_2 , Cl^- ions, and variances in the pH. The corrosion cells may either be macro or micro. The anode and cathode are on two separate pieces of reinforcement in a macro-cell. In a micro-cell the anode and cathode areas are close together on the same piece of reinforcement steel. Micro-cell corrosion is the more prominent form of corrosion cell found in reinforced concrete.

The flow of current from the anode to the cathode area produces OH^- ions through the reaction of oxygen and water. These migrate to the anode where the dissolution of the iron results in the formation of anions (Fe^{++}) which combine with the OH^- ions in the pore water solution to produce oxidation products or rust. Examples of these oxidation states include $Fe(OH)_2$ and $Fe(OH)_3 \cdot 3H_2O$ which have 4 to 6 times the volume of metallic iron, respectively [11].

The expansion of the oxidation products creates pressure within the concrete structure which can lead to the cracking or spalling of the concrete cover. Additionally, this reaction reduces the strength of reinforced concrete by decreasing the cross-sectional area of the reinforcing steel and the bond strength at the interface between the steel and concrete.

2.3 Factors Controlling the Rate of Corrosion

Until the concentration of Cl^- ions reaches a threshold

level corrosion will not be initiated. The threshold concentration has been estimated at 1.2 lbs/yd³ [19] or 0.3% by weight of the cement content [20]. Other research has indicated that the threshold may be based on the ratio of Cl⁻ to OH⁻ ions in the pore solution. A threshold ratio of 0.6 has been estimated for the Cl/OH ratio [21].

Chlorides may be introduced into the concrete during mixing or through environmental exposure. Calcium chloride has been used as an admixture to accelerate the set of concrete. Chlorides may also be present in the aggregates or mix water in coastal regions. The majority of chloride induced corrosion is the result of the ingress of chlorides into the hardened concrete through environmental exposure.

Diffusion is the primary mechanism of chloride ion ingress. The time to initiate corrosion by diffusion is governed by the driving concentration, the permeability of the concrete which is a function of the w/c ratio, and the depth of cover [19]. Additionally, chlorides are rapidly transferred to the reinforcing steel through cracks in the cover concrete. These cracks are typically the result of subsidence cracking in the fresh concrete [22].

Since the cathodic reaction is the reduction of oxygen, the diffusion of oxygen to the cathode can control the rate of reaction. Oxygen is readily available in bridge structures [20], unless the concrete is saturated with water. In this case the supply of oxygen is limited by its

diffusion rate through water.

Another limiting factor can be the resistivity of the concrete to the ionic current. Dry concrete has a resistivity of $1 \times 10^9 \Omega\text{-cm}$, while water saturated concrete has a resistivity of $1 \times 10^4 \Omega\text{-cm}$ [20]. Therefore, moisture content plays an important role in the rate of corrosion. Both carbonation and chloride induced corrosion occur at a maximum rate in concrete with a 60% relative humidity (RH) [23].

2.4 Techniques for Measuring Corrosion of Steel in Concrete

Techniques have been developed which provide the engineer with information on the potential for corrosion and the corrosion activity of reinforced concrete. Some methods indicate the potential for corrosion while others measure the factors affecting the rate of corrosion, such as chloride content and concrete resistivity. Other methods attempt to measure the actual corrosion rate.

When combined, the data allows the engineer to assess the corrosion state of a structure or monitor the performance of new repair techniques or treatments.

2.4.1 Chloride Measurement

Chloride measurements as a function of depth are valuable to the engineer to determine the degree of chloride contamination of the concrete. The concrete sample can be

collected either by dry coring or drilling. Once the powdered sample is digested in an acid solution, the chloride content can be determined by titration versus AgCl in accordance with AASHTO T 260-84, "Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials," or through the use of a specific ion probe [24].

2.4.2 Potential Survey

A potential survey can be used on a reinforced concrete structure to estimate the likelihood of active corrosion and delineate the anodic and cathodic areas. Potential measurements are determined relative to a reference or standard electrode. The potential of a standard electrode is based on the tendency for a reduction reaction to occur at that electrode [25]. The corrosion potential (E_{corr}) is determined by measuring the potential difference, between two electrodes or half-cells. A standard electrode acts as a reference or zero point from which the likelihood of a reduction ($+E_{\text{corr}}$) or oxidation ($-E_{\text{corr}}$) reaction can be measured. The potential of the standard hydrogen electrode (SHE) is set at zero; a comparison between the SHE and other common half-cells is shown in Table 1. Silver/silver chloride electrodes (Ag/AgCl) are sensitive to the $\text{OH}^-:\text{Cl}^-$ ratio, and are subject to drift [26]. Therefore, comparisons to other standard cells must be made with caution.

Table 1. Reference Half-Cells [25,27,28]

Reference Half-Cell	Reaction	SHE Scale at 25°C
Standard Hydrogen Electrode (SHE) (in 1.2 M HCl)	$2\text{H}^+ + 2\text{e}^- \rightleftharpoons \text{H}_2$	0.000 V
Copper Sulphate Electrode (CSE) (in Saturated CuSO_4 solution)	$\text{Cu}^{++} + 2\text{e}^- \rightleftharpoons \text{Cu}$	+0.300 V
Silver/Silver Chloride Electrode (in 1 M KCl)	$\text{AgCl(s)} + \text{e}^- \rightleftharpoons \text{Ag} + \text{Cl}^-$	+0.235 V
Silver/Silver Chloride Electrode (0.1 M Cl ⁻)	$\text{AgCl(s)} + \text{e}^- \rightleftharpoons \text{Ag} + \text{Cl}^-$	+0.288 V

ASTM C-876-87, "Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete," describes a procedure for measuring the corrosion of activity of reinforced concrete structures. The probability of corrosion activity measured using a copper sulphate electrode (CSE) is given as [29]:

$E_{\text{corr}} > -0.20 \text{ V CSE} \rightarrow 90\% \text{ probability of no corrosion activity}$

$-0.20 > E_{\text{corr}} > -0.35 \text{ V CSE} \rightarrow \text{corrosion activity uncertain}$

$E_{\text{corr}} < -0.35 \text{ V CSE} \rightarrow 90\% \text{ probability of corrosion activity}$

Corrosion potentials should only be used as an indicator of corrosion activity, not a measurement of corrosion activity or rate of corrosion. The actual

potential measured is influenced by environmental conditions and may be misleading [30].

2.4.3 Corrosion Rate Measurement

Non-destructive methods are used to measure the corrosion rate of steel in concrete. These tests provide quantitative evidence of corrosion activity. The current which flows between the anodic and cathodic sites of the corrosion cell is proportional to the rate of corrosion according to Faraday's First Law:

$$R = kI_{corr} \quad (5)$$

where,

R = rate of corrosion (grams/second)

k = electrochemical equivalent (grams/Coulomb)

I_{corr} = corrosion current (amperes)

The impedance resistance technique is the most common method for measuring i_{corr} . In 1958, Stern and Geary [31,32] defined polarization resistance as follows:

$$R_p = \left(\frac{\Delta E}{\Delta I} \right)_{\Delta E \rightarrow 0} \quad (\text{ohm}\cdot\text{cm}^2) \quad (6)$$

Which states that by applying a potential step, ΔE , of 10-20 mV and measuring the current response, ΔI , you can determine the resistance of the cell. The instantaneous corrosion current (i_{corr}) is related to the polarization resistance through the Tafel Slopes as follows:

$$i_{corr} = \left[\frac{\beta_a \beta_c}{2.3 (\beta_a + \beta_c)} \right] \cdot \frac{1}{R_p} = \frac{B}{R_p} \quad (7)$$

where,

β_a = anodic Tafel slope

β_c = cathodic Tafel slope

B = Stern-Geary constant

The value for B varies from 13 to 52 mV for most electrochemical cells [33]. When applying the polarization resistance technique to reinforced concrete, the measured polarization resistance must be corrected to allow for the high resistance of the concrete as shown in Equation (8) [34].

$$R_p = R_{p,measured} - R_{concrete} \quad (8)$$

where,

$R_{concrete}$ = resistance of the concrete (ohm·cm²)

If $R_{conc.}$ cannot be measured directly, it can be accounted for using electronic techniques such as IR adjustment or current interrupt.

The two most common methods for measuring impedance resistance are the D.C. linear polarization method, and the A.C. impedance method.

Generally, three electrodes are employed in the linear polarization method, the working electrode, the reference electrode, and the counter electrode. The working electrode is the anodic area of the reinforcing steel within the

influence area of the counter electrode. The reference electrode is used to determine the equilibrium potential of the cell, and to sense the potential changes resulting from current applied through the counter electrode.

The current supplied to the counter electrode is generally controlled by a potentiostat. A slow potential sweep, from the equilibrium potential, is applied by varying the current output to the counter electrode. The slope of the potentiodynamic polarization curve, which relates ΔE to ΔI , is the polarization resistance [35]. The linear polarization resistance can also be measured by applying a small constant current (galvanostatic) and measuring ΔE as a function of time, or by applying a constant potential (potentiostatic) and measuring ΔI as a function of time [36].

The estimation of the area of polarization, and the potentiostat scan rate effect the accuracy of linear polarization methods. Additionally, the measured value of the polarization resistance (R_p) must be corrected for the ohmic drop of the concrete between the reference electrode and the working electrode.

Estimating the actual area of polarization presents a second problem. The measured value of R_p is dependent on the area of polarization and can have a significant effect on the i_{corr} reading [37]. Some devices use an auxiliary guard ring electrode to confine the polarization current to

a known test area.

Studies have shown that the measured value of R_p is dependent on the scan rate employed by the potentiostat due to a lag in the potential response [36]. Slow scan rates give the best results but may be impractical for field use.

More accurate values of R_p and R_{concrete} can be obtained by using the A.C. impedance method. A potentiostat and frequency response analyzer (Fast Fourier Transform) are required to perform A.C. impedance measurements. Millard et al state that, "Measurements are typically taken using a sine wave perturbation of amplitude 20 mV r.m.s. over a range of frequencies from 1 kHz to 10 mHz" [36].

The response is a sinusoidal signal with a different frequency corresponding to ΔI . Multiple samples of the response are taken at each frequency to suppress noise. The ratio of the perturbation to the response is defined as the impedance (Z). Resistance and capacitance elements are used to model the impedance circuit as presented in Equation 9 [33]:

$$Z = R_e + \left[\frac{R_T}{(1 + j\omega CR_T)} \right] \quad (9)$$

where,

R_e = electrolyte (concrete) ohmic resistance

C = capacitance of the electrode

ω = angular frequency ($\omega = 2\pi f$)

j = imaginary unit, $\sqrt{-1}$

R_T = transfer resistance, equivalent to R_p

The impedance, which is frequency dependent, can be plotted as a semi-circle in a Nyquist complex plot. The diameter of the semi-circle is equal to the polarization resistance, R_p . The polarization resistance may also be obtained from the difference between the high frequency range which is approximately equal to the concrete resistance, R_c and the low frequency limit which is approximately equal to the sum of the polarization resistance and the concrete resistance, $R_c + R_T$. The data is presented in a Bode plot, where the impedance module and the phase shifts are plotted as a function of the frequency [33].

Unfortunately, depending on the lower frequency limit, a single test can take 30 minutes or more making the device impractical for field use. A.C. impedance also suffers from an uncertain area of polarization in actual structures.

2.5 Corrosion Inhibitors

Corrosion inhibitors are used to prevent or delay corrosion of metals exposed to a potentially corrosive environment. Corrosion inhibitors are generally classified as anodic, cathodic or mixed inhibitors according to their function.

Anodic inhibitors reduce the rate of reaction at the

anode. Often they react with the corrosion products to form a protective coating on the metal surface.

Cathodic inhibitors act to smother the reaction at the cathode. Griffin states, "Reactive products of cathodic inhibitors do not bond to the metal surface as tightly as those of anodic inhibitors and are, therefore, less effective," [38]. Cathodic inhibitors act indirectly since they do not prevent metal dissolution.

Mixed inhibitors effect both the anodic and the cathodic sites. This is especially advantageous in reinforced concrete due to the prominence of micro-cell corrosion.

2.5.1 Adsorbed Layer Inhibitors

Dean et al [39], classify inhibitors by the following mechanisms of inhibition: adsorbed layer formers, oxidizing inhibitors-passivators, conversion layer formers, and scavengers. Adsorbed layer formers are organic inhibitors which strongly adsorb to the metal surface and interfere with the anodic or cathodic reactions in the area of adsorption. The effectiveness of these inhibitors is measured as a percent reduction as shown in Equation 10 [38].

$$\%inhibition = 100\left(\frac{R-R^*}{R}\right) \quad (10)$$

where,

R = corrosion rate without the inhibitor

R^* = corrosion rate with the inhibitor

The percent inhibition is a function of the surface coverage of the adsorbed layer.

Nitrogen is usually the active atom in an adsorbed layer inhibitors acting in a non-acid electrolyte on steel. Typical compounds of nitrogen used as inhibitors are organic nitrates and amines. The bond strength of the adsorbed layers is due to the nitrogen atom's high density of electrons, and ability to form co-ordinate bonds [40].

Vapor phase inhibitors (VPI or Volatile Corrosion Inhibitor VCI) are similar to adsorbed layer inhibitors. Miksic [41] provides the following definition: "Volatile Corrosion Inhibitors are secondary electrolyte layer inhibitors that possess appreciable saturated vapor pressures under atmospheric conditions, thus allowing significant vapor phase transport of the inhibitive substance." Aliphatic and cyclic amines and nitrites with a high vapor pressure typically make up these inhibitors [40]. Rozenfeld [42] provides specific compounds for the interested reader.

2.5.2 Oxidizing Inhibitors

Oxidizing inhibitors or passivators are another form of barrier inhibitor which act by shifting the electrochemical potential of the corroding metal such that an insoluble oxide or hydroxide forms on the metal surface [39]. Sodium nitrite and chromates are examples of this inhibitor.

Another form of passivators are metal soaps. Metal soaps form from the basic pigments (metal oxides) and oxidation products of oils such as cinnamic and pelargonic acid [40]. These form passivating films on the metal surface.

2.5.3 Conversion Layer Inhibitors

Conversion layer inhibitors form insoluble compounds on the metal surface without oxidation. In neutral or basic solution, Dean *et al* [39] state, "the presence of calcium and magnesium ions also inhibit corrosion by the formation of an insoluble calcareous scale on the metal surface." This is similar to one of the passivation theories suggested for steel in concrete.

2.5.4 Scavengers

Finally, scavengers act as neutralizing inhibitors by removing concentrations of corrosive materials such as the Cl^- ion.

2.5.5 Dangerous Inhibitors

The effect of corrosion inhibitors is generally concentration dependent, such that some areas may be unprotected if an insufficient quantity of the inhibitor is present. From this arises the concept of dangerous inhibitors. Dangerous inhibitors increase the rate of attack in unprotected areas, similar to the haloing effect sometimes produced around patches due to the increase in the cathodic area after the repair. Most anodic inhibitors are

dangerous inhibitors [38].

2.5.6 Current Use of Inhibitors in Concrete

In concrete, corrosion inhibitors are typically admixtures used to prevent the reinforcement steel imbedded in the concrete from corroding. Calcium nitrite is the only chemical to be used to any extent commercially as an inhibitor [17]. ACI 212.3R [43] reports other chemicals which have been tested in the past.

3.0 EXPERIMENTAL DESIGN

3.1 Introduction to Experimental Design

The task of developing repair and rehabilitation techniques using corrosion inhibitors for reinforced concrete structures was accomplished in three phases:

- I) Evaluation of Corrosion Inhibitors
- II) Development of Field Treatment Specifications
- III) Estimation of Service Life

Initial corrosion inhibitor evaluations were carried out on 1 ft x 1 ft reinforced concrete specimens. Thirty-six specimens with varied ranges of corrosion activity were treated. Specimens were cast containing 1 or 2 triad(s) of reinforcing steel (rebar). After initial curing the specimens were alternately ponded with a 6% by weight salt water solution and allowed to air dry to induce corrosion.

Half-cell measurements were initially used to monitor the specimens corrosion activity. Once a drop in the corrosion potential indicated the initiation of corrosion activity, an unguarded linear polarization device, the 3LP, was used to monitor the corrosion rate. Chloride measurements were taken at the bar level prior to treatment.

Collins [10] identified 5 potential inhibitors, 3 commercial and 2 experimental materials used in four separate treatment methods, two of the inhibitors are used

in combination. The inhibitors were applied in a 3 step treatment process. First, the chloride contaminated cover concrete was removed to the bar level. Next, an inhibitor was surface ponded on the specimen. A series of specimens were dried to 180° F. at a depth of ½" below the bar level prior to inhibitor ponding. Finally, a 2" modified overlay was applied. The overlay concrete was tested for slump, air content, and compressive strength in accordance with ASTM specifications. Control specimens were also prepared for comparison purposes.

Once the treated specimens had cured, salt water ponding and corrosion rate measurements resumed. Corrosion rate measurements were used to determine which treatments would continue to be studied in Phase II.

Overlay bond strength tests were performed on 16 well cured small scale specimens prior to the treatment of the large deck specimens. Due to the bond reduction effects of 2 inhibitors, additional specimens were treated in an attempt to identify a procedure which would provide an acceptable bond between the original concrete and the overlay.

The large scale specimens treated in Phase II were salvaged from a bridge deck removal project on I-80 in Pennsylvania. Three combinations of inhibitors and modified overlays were applied. Both the 3LP and a linear

polarization device with a guard ring electrode (Gecor Device) were used to monitor the corrosion rate of these specimens.

Freeze-Thaw durability tests were performed on the modified overlay concrete used in Phase II. Concrete samples were evaluated by ASTM C-666-84, "Resistance of Concrete to Rapid Freezing and Thawing," Procedure A.

3.2 Small Scale Specimen Design

3.2.1 Construction Details

Specimens with both 1 and 2 triads of reinforcement steel were cast for evaluation. Each triad consisted of three electrically connected pieces of rebar, one, placed at the specified cover depth, acted as the anode, and two acted as the cathode placed $1\frac{3}{4}$ " below the anode. Forms were constructed for twelve specimens of each configuration. 36 specimens were cast by previous investigators; 24, 1 triad and 12, 2 triad with 1 set of each having a cover depth of 2" and the second set of 1 triad having a 1" cover depth. The dimensions for the 1 and 2 triad configurations are provided in Figures 1 and 2 respectively.

The forms were made of $\frac{3}{4}$ " BC grade exterior plywood fastened with drywall screws. The reinforcement steel was supported by plywood spacers placed in two ends of the form, $\frac{5}{8}$ " diameter holes were drilled in the spacers to accommodate

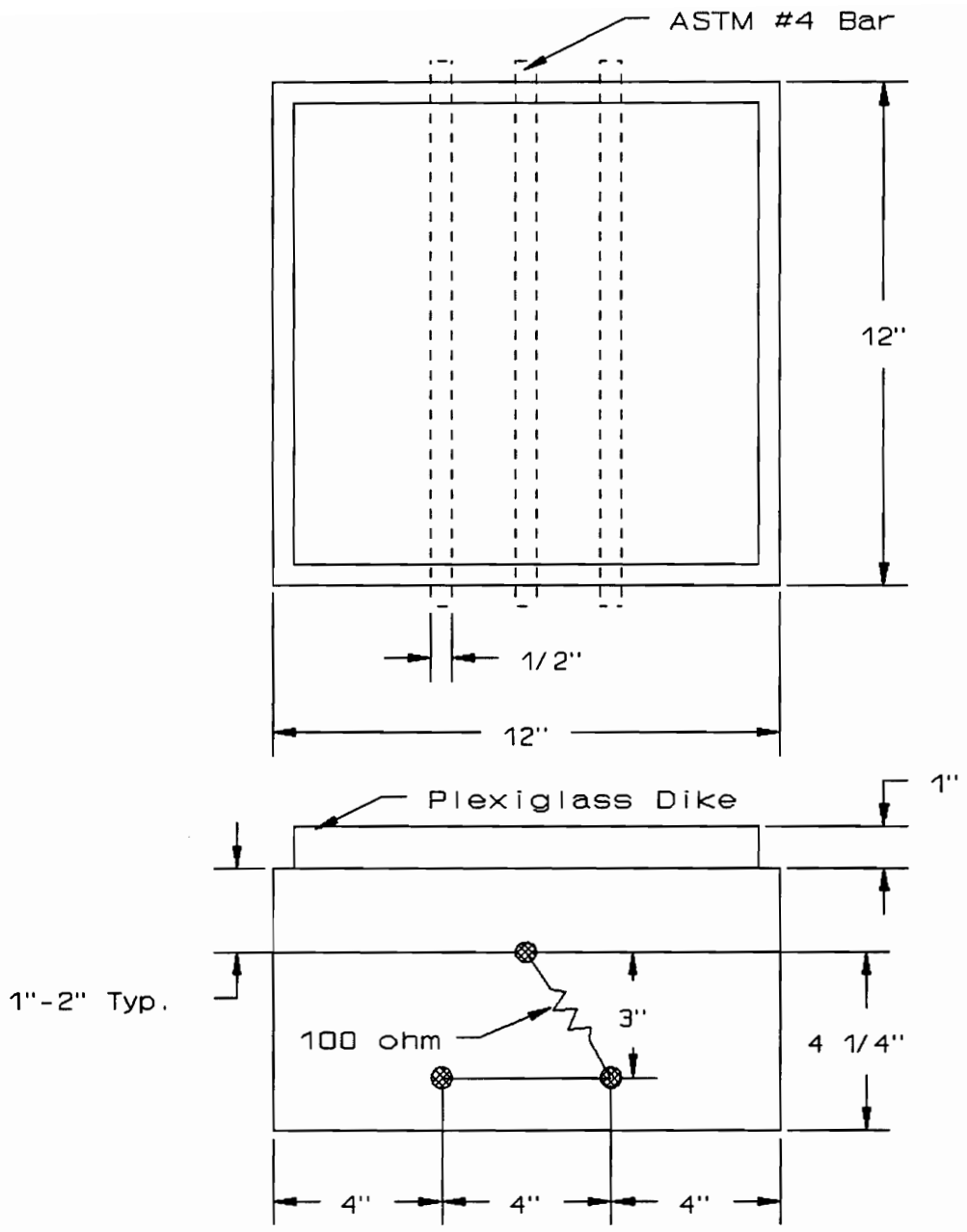


Figure 1. One Triad Specimen Configuration

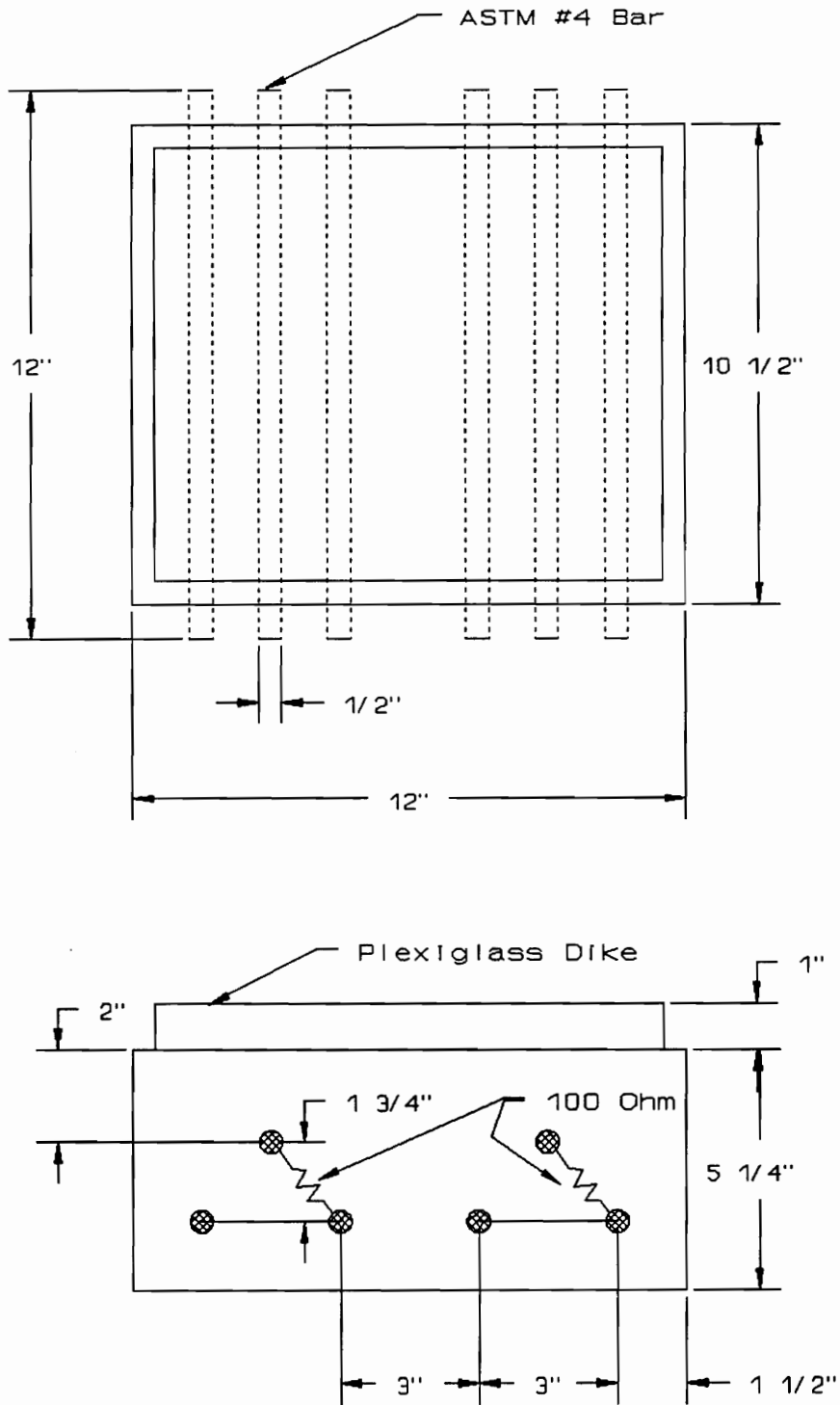


Figure 2. Two Triad Specimen Configuration

the $\frac{1}{2}$ " diameter rebar. New spacers were cut to provide the 1" cover for the second set of 1 triad specimens.

ASTM grade 60 #4 bar with a nominal 0.5" diameter was used as reinforcing steel. The rebar was cut into 12" lengths with a Milwaukee cut-off saw. The bars were cleaned with hexane and oven dried to remove any manufacturing latencies. The ends of each bar were covered with electroplating tape to provide a known length of exposed corrodible steel, approximately 7 $\frac{1}{4}$ ".

Prior to placing the concrete, the forms were twice coated with form oil and the rebar placed in the holding spacers. A type T thermocouple (copper/constantan) was attached to the center of the top rebar with electroplating tape.

3.2.2 Specimen Casting

To minimize the likelihood of subsidence cracking, the specimens were cast in an inverted position. The top layer of reinforcement was placed such that it was the specified clear cover distance above the bottom of the form. A vibratory table was used to consolidate the fresh concrete.

The first set of 1 triad, 2" cover specimens were cast with ready-mix concrete supplied to meet Virginia A4AE Bridge Deck Air Entrained concrete specifications. A set of 2 triad, 2" cover specimens were cast 20 days later. The ready-mix concrete was produced by the same supplier to

similar specifications. The mixture proportions are presented in Appendix A, Table A-1.

The 1 triad, 1" cover depth specimens were cast 83 days later. The concrete cover was reduced to decrease the time necessary for the chlorides to diffuse to the top reinforcing steel and initiate corrosion. The concrete for this group of specimens was hand batched in a 2 ft³ pan mixer. Four batches were required to produce the 12 specimens. The mixture proportions and the tested parameters of the fresh and hardened concrete are provided in Table A-2, Appendix A.

3.2.3 Specimen Curing and Preparation

Once the concrete was placed and consolidated, the samples were covered with moist burlap and polyethylene sheeting and allowed to cure for 3 days prior to the form removal.

One end of each rebar was tapped to accommodate a No. 10-24 x 3/8" machine screw. The top and bottom layer of steel in each triad were connected with a 100Ω resistor and the 2 bars in the bottom layer were connected with 18 gauge wire as shown in Figures 1 and 2. A male subminiature connector was attached to the type T thermocouple leads.

The sides of the specimens were coated with SURE-POXY LMLV epoxy to reduce the diffusion of oxygen and water-vapor

simulating the boundary conditions on an actual bridge component.

3.3 Corrosion Initiation

3.3.1 Chloride Exposure

The specimens were ponded with 400 ml of a 6% by weight NaCl solution on a weekly basis. The salt water was allowed to stand on the specimens for 3 days, after which, it was removed with a wet/dry vacuum. The specimens were then allowed to air dry for 4 days before the cycle is repeated. Plexiglass dikes 10"x10"x2" were attached to the top of each specimen with silicone caulk to contain the salt water solution. The specimens were stored in an insulated conditioning room to minimize temperature fluctuations.

One day after the removal of the salt water, half-cell potentials measurements were taken on each specimen. Three measurements were taken along the surface above each bar using a Cu-CuSO₄ (CSE) reference half-cell and hand held multimeter in accordance with ASTM C-876-87. A specimen was considered to be actively corroding when the mean potential value was more negative than -350 mV (see section 2.4.2).

3.3.2 Corrosion Rate Measurements

After the probable initiation of corrosion, the specimen's corrosion current was measured using a three electrode linear polarization device (3LP) developed by K.C. Clear, Inc. The rebar acts as the working electrode and a CSE pen cell is used as the reference cell. The polarization current is applied through copper wire screening contained in the contact sponge. The corrosion current (i_{corr}) is calculated using the Stern-Geary equation (Equation 7). The Tafel slope constant was estimated from Clear's research as $B = 40.76 \text{ mV}$ [44]. According to Faraday's Law, the i_{corr} is directly proportional to the corrosion rate. Thus, i_{corr} measurements provide a relative indication of the corrosion activity in the specimens.

Further research by Clear correlated the i_{corr} measurement with the time to expected damage of the concrete. These guidelines were used to group the corrosion activity of the specimens prior to treatment as shown in Table 2 [44].

After the first year of salt water ponding cycles, 3LP measurements were routinely taken on all of the specimens, even those with potentials more noble (less negative) than -350 mV CSE .

Table 2. i_{corr} Correlated to Time to Expected Damage

i_{corr} mA/ft ²	Time to Expected Damage
$i_{\text{corr}} < 0.20$	None Expected
$0.20 < i_{\text{corr}} < 1.0$	Possible in 10-15 years
$1.0 < i_{\text{corr}} < 10$	2-10 years
$i_{\text{corr}} > 10$	< 2 years

3.3.3 Chloride Concentration Measurements

Chloride measurements as a function of depth were also taken from the specimens to provide an additional indication of the likelihood of corrosion activity. Powdered concrete samples were collected in $\frac{1}{2}$ " increments starting at a depth of $\frac{1}{4}$ ". The samples were collected using a rotary impact hammer equipped with a $1\frac{1}{8}$ " masonry bit. The sample was obtained with a vacuum assisted collection device through a hole in the tip of the bit.

The Cl^- ion concentration of the sample was measured using the specific ion electrode method primarily developed by Mark Henry [24]. The method uses an acid based solution to digest 3 grams of the sample. A dilute NaCl solution is added to the digested solution to reduce temperature effects and provide a background Cl^- concentration within the probes measurement range. The Cl^- ion concentration is then measured with a specific ion probe. The probe reading in mV

is converted to lbs/yd³ of chloride using a calibration equation.

The chloride threshold necessary for the initiation of corrosion was considered to be 1.2 lbs/yd³ for this project.

3.4 Materials

3.4.1 Cement

Type I Portland cement was used for all of the concrete mixtures in this study. The cement was produced by Taramac Cement Co. in Roanoke, Virginia.

3.4.2 Coarse and Fine Aggregates

The coarse aggregate was ¾" crushed limestone quarried by Atco Stone Co, Blacksburg, Virginia. The fine aggregate was a natural sand processed in Wytheville, Virginia. The gradation and physical parameters of the aggregates are provided in Appendix A, Tables A-3 and A-4.

3.4.3 Chemical Admixtures

An air entrainment agent, MBVR, produced by Master Builders Inc. was added to all of the mixes with the exception of the LMC mix to provide freeze-thaw durability.

Upon the recommendation of the manufacturer, an initial

set retarder and high range water reducer were added to the overlays modified with DCI. The retarder, Daratard-17, conforms to ASTM C-494 Type B and D specifications. The water reducer, Daracem-100 conforms to ASTM C-494 Type A,F Specifications. Both products were manufactured by W.R. Grace.

DPS Modifier A produced by Dow Chemical Company was used as the latex admixture for all latex modified concrete overlays.

3.4.4 Corrosion Inhibitors

In previous research conducted by Collins [10], 7 corrosion inhibitors and 2 sealers were evaluated to determine their effectiveness in reducing corrosion rates in reinforced concrete specimens. The following 5 corrosion inhibitors were identified as showing promising results and recommended for further study:

1. Alox 901 (proprietary oxygenated hydrocarbon produced by the partial oxidation of an aliphatic hydrocarbon): An organic inhibitor which is thought to form a protective film by conversion to a metallic soap.

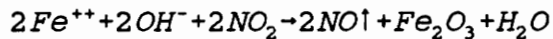
2. Cortec VCI-1337 [MCI-2020] (a proprietary blend of surfactants and amine salts in a water carrier): A secondary electrolyte layer inhibitor with appreciable vapor pressure under atmospheric pressure or 'volatile corrosion inhibitor'

(VCI) [41]. The product is designed to migrate in a vapor phase and adsorb on a metallic surface forming a monomolecular film at both anodic and cathodic sites.

This product was designed to be applied by surface injection and spray application.

3. Cortec VCI-1609 [MCI-2000] (proprietary alkanolamines): This product is designed to migrate and inhibit in a manner similar to VCI-1337 with the exception that it is a concrete admixture.

4. DCI (calcium nitrite, $\text{Ca}(\text{NO}_2)_2$): The nitrite ions in this inhibitor compete with the chloride ions for the ferrous ions at the anode. The nitrite and ferrous ions react as follows:



This reaction forms a stable passive layer on the reinforcement steel [45].

DCI is designed as a concrete admixture for corrosion inhibition. Unlike its predecessor sodium nitrite, it does not adversely affect the strength gain of the concrete. However, it does act as a strong accelerator, normally requiring the addition of a water reducer and retarder in the mix design.

5. Sodium tetraborate ($\text{Na}_2\text{B}_4\text{O}_7$): An experimental inhibitor which forms a protective layer on metal surface

through the reaction of borate and oxygen. This reaction appears to be highly dependent on the pH of the pore solution.[46]

Tests indicate that the borate ion is more mobile in concrete than the chloride ion. This would indicate an ability to migrate faster to the rebar in concrete [47].

3.5 Treatment of Small Scale Specimens

3.5.1 Treatment Matrix

The corrosion inhibitors were divided into four cells of surface ponding agents and concrete admixtures. The application concentrations were based on previous research by Collins [10]. An untreated latex modified overlay was included as a control in each cell combination. The treatments were applied to specimens with the chloride contaminated cover concrete removed to the rebar level. Table 3 presents the inhibitor combinations and application concentrations.

Three methods of application were used to apply the ponding agents. These include: 1 day ponding, 2 day ponding, and 1 day ponding of specimens dried to 180° F at $\frac{1}{2}$ " below the top reinforcement.

Additionally, 3 overlay systems were applied to specimens for which the chloride contaminated cover concrete

was not removed. These systems were: 1" LMC overlay, 2½" bituminous concrete overlay with a waterproof membrane, and a thin polymer overlay.

In order to investigate the effectiveness of the treatments on varying corrosion rates, the corroding specimens were divided into 3 categories (see Figure 4) based on time to

Table 3. Treatment Combinations

Surface Ponding Agents	Overlay Admixtures
0.1M Alox 901 in Denatured Ethyl Alcohol	Dow Latex 196 lbs / yd ³
Cortec VCI-1337	Cortec VCI-1609 1 pint / yd ³
0.1M DCI (Calcium Nitrite) in Water	DCI 6 gallons / yd ³
0.1M Sodium Tetraborate in Water	0.1M Sodium Tetraborate in Mix Water
None	Dow Latex 196 lbs / yd ³

expected damage as correlated to i_{corr} (see Table 2). The matrix shown in Figure 4 was designed to incorporate the effect of different treatment procedures and materials on the range of corrosion rates.

The specimens were treated in 3 separate groups. The first group included the blocks with 1 and 2 day ponding with low corrosion rates, 1 day ponding of dried specimens

Time to Expected Concrete Damage in Years, Based on Icorr			
	10-15	2-10	<2
Ponding 1 Day	Alox 901/LMC Cortec 1307/1609 DCI/DCI Sodium Borate * LMC Control	Alox 901/LMC Cortec 1307/1609 DCI/DCI Sodium Borate * LMC Control	Data Not Required
Ponding 2 Day	Alox 901/LMC Cortec 1307/1609 DCI/DCI Sodium Borate * LMC Control	Data Not Required	Data Not Required
Dried 180 F at 1/2" Below Bar Pond 1Day	Alox 901/LMC Cortec 1307/1609 DCI/DCI Sodium Borate * LMC Control	Alox 901/LMC Cortec 1307/1609 DCI/DCI Sodium Borate * LMC Control	Alox 901/LMC Cortec 1307/1609 DCI/DCI Sodium Borate * LMC Control
Controls	1" LMC Overlay WR Grace Memb. w/ 2 1/2" BC Thin Polymer Overlay	Untreated	Data Not Required

* - For LMC Controls, Concrete Removed to Bar Level

Figure 4. Specimen Treatment Matrix Ponding Material/Admixture Material

with high initial corrosion rates and the overlay controls.

After monitoring the i_{corr} measurements of this group for 2 months, it was determined that 2 day ponding did not have a greater effect on corrosion rates as compared with 1 day ponding. Additionally, field performance indicates that the control overlays do not provide sufficient retardation of high initial corrosion rates. Therefore, further treatments with 2 day ponding and the control overlays were eliminated.

The second treatment group included 1 day ponding and 1 day ponding with drying of specimens with medium initial corrosion rates. The third treatment group consisted of 1 day ponding of dried specimens with low initial i_{corr} measurements.

3.5.2 Removal of Chloride Contaminated Concrete

Prior to the application of the corrosion inhibitors, the chloride contaminated cover concrete was removed to the top layer of reinforcing steel. First the ponding dikes were removed. Then the top surface of the specimen was sawed perpendicular to the rebar at $\frac{1}{2}$ " intervals using a water-cooled masonry saw with a 1/16" thick diamond blade. The depth of cut was set to avoid contact with the rebar. Unfortunately, some bars were nicked due to uneven specimen bottoms.

The sawed cover concrete was removed with a hammer and masonry chisel. This continued until a relatively even surface, which would simulate the surface left after milling a deck, was obtained.

3.5.3 Specimen Drying

After the cover concrete was removed, a $\frac{1}{4}$ " diameter hole was drilled in the bottom of the specimen to be dried. The hole was drilled to a depth equal to $\frac{1}{2}$ " below the top rebar. A type T thermocouple with glass braid insulation was installed in the hole before the hole was sealed with duct seal.

The specimens were then placed on a sand bed under a steel frame which supported the heaters. The sand was used to level the specimens. Fiberglass insulation was placed around the sides of the specimens to simulate the single surface heating which would occur on a bridge component such as the deck. The thermocouple leads were also covered with insulation and connected to a switching box outside the frame.

Propane fueled infrared heaters were suspended at a height of 16" above the specimen's top surface. Once the heaters were lit, the specimen's temperature was recorded at 2 minute intervals. A surface probe was used to monitor the approximate temperature at the surface of the specimens.

The heaters were shut off when the mean temperature of the specimens at the measurement depth reached 170° F. The temperatures were then monitored for an additional 30 minutes. Drying temperatures as a function of time for each group of specimens are presented in Figures C1-C3, Appendix C.

Once the heaters had cooled sufficiently to allow access, the specimens were covered with fiberglass insulation to help prevent thermal cracking.

3.5.4 Inhibitor Application

The corrosion inhibitors, designated as surface ponding agents, were applied to the surface of the specimens for the time period specified in the treatment matrix, prior to their overlay. The ponding agent was contained by the sealed forms to be used for the placement of the overlay. The corrosion inhibitor was poured into the forms to a depth of $\frac{1}{4}$ ".

The forms were constructed of $\frac{5}{8}$ " BC grade exterior plywood fastened with $1\frac{1}{4}$ " drywall screws. The forms were 4" in height on the sides of the specimen parallel to the reinforcement steel and overlapped the side of the specimen by 2". The sides perpendicular to the bar were 2" in height and rested on the rebar protrusions. This provided an overall cover depth of 2" after overlay. The insides of the

forms were coated with an epoxy to provide a nearly non-absorbent surface. The form-specimen interface was sealed with silicone caulk.

At the end of the specified ponding period, the excess inhibitor was removed with a wet/dry shopvac. Dry cement was dusted onto the surface of the specimens treated with Alox 901 to help absorb residual petroleum products. These specimens were then placed outdoors in direct sunlight for 1 hour after which time the surface was blasted clean of loose particles with compressed air.

3.5.5 Inhibitor Modified Overlays

The batch proportions used for the modified overlay mixtures are presented in Appendix A, Tables A-5 through A-8. The initial mixes were modified with progressive treatment groups to provide improved strength, workability, and freeze-thaw durability. The overlay concrete was batched in a 2 ft³ pan mixer.

A thick grout was applied to the surface of each specimen immediately prior to placing the concrete. The grout was obtained by sieving out the coarse aggregate from a portion of the concrete mixture.

The specimens were placed on a vibratory table to consolidate the overlay concrete. The overlaid specimens

were covered with moist burlap and polyethylene sheeting. The overlays were moist cured for 3 days. After curing, the sides of the specimens were recoated with SURE-POXY LMLV epoxy and the ponding dikes reinstalled. Until 28 days after placement, the specimens were ponded with clear water. The slump, air content, and unit weight of the plastic overlay concrete was measured. The slump was measured in accordance with ASTM C-143-78, "Slump of Portland Cement Concrete." The air content and unit weight were measured according to ASTM C-231-82, "Air Content of Freshly Mixed Concrete by the Pressure method," with a Type B Meter.

Six 4"x6" cylinders were cast from each concrete batch. The cylinders were cured at 70° ±2° F and 100% relative humidity. The compressive strength of pairs of cylinders were measured at 1, 7, and 28 days in accordance with ASTM C-39-86, "Compressive Strength of Cylindrical Concrete Specimens."

Fresh and hardened concrete mixture characteristics are summarized in Appendix A, Tables A-5 through A-8.

3.5.6 Control Overlays

Three control overlays were used for comparison purposes: 1" Latex Modified Concrete (LMC) overlay, thin polymer overlay, and 2½" Bituminous concrete (BC) overlay

with waterproof preformed membrane. The 1" LMC overlay was placed in the same manner as the above treatments.

A non-skid flexible epoxy-urethane co-polymer, MARK-163 Flexogrid, produced by Polycarb was used as the binder for the thin polymer overlay. The application procedure is described in Appendix A, Table A-9A. The aggregate was a Morie #3 basalt. Particle size gradation and physical characteristics of the aggregate are given in Appendix A, Table A-9B. The overlay was applied in accordance with the manufacturer's specifications.

W.R. Grace's Bituthane preformed membrane system was used with the bituminous concrete overlay. The membrane was applied according to the manufacturers specifications. The bituminous concrete, a Virginia SM-5 surface mixture, was heated to a temperature of 270° F and then compacted with a hand tamper in a 2½" plywood form built around the specimen. The mixture proportions for the bituminous concrete are presented in Appendix A, Table A-10.

3.6 Post-Treatment Corrosion Monitoring

Chloride exposure to a 6% NaCl solution applied on a 3 day ponding and 4 day drying cycle resumed 28 days after the overlay placement. i_{corr} measurements were taken with the 3LP on a regular basis to monitor the corrosion activity. The

readings were taken on the second day of the drying cycle.

3.7 Determination of Bond Strength

The bond strength between the modified overlay and base concrete was measured to determine the effects if any of the corrosion inhibitors. A poor bond strength would indicate that the overlay would probably delaminate and spall under traffic loading and freeze-thaw cycles.

The bond strength was measured using a method described in ACI 503R [48]. The procedure and equipment are described in Appendix B.

3.8 Treatment of Large Scale Specimens

The large scale specimens were salvaged from a bridge deck replacement project on I-80 in Pennsylvania. The 8" thick, large scale specimens ranged in size from 13.5 to 22.7 ft². The slabs were stored indoors for a month prior to treatment to minimize temperature fluctuation, and covered with moist burlap and polyethylene sheeting to prevent moisture loss.

3.8.1 Pre-Treatment Corrosion Monitoring

Prior to treatment a corrosion survey was conducted on the slabs similar to that which would be conducted on an

actual bridge deck. The survey included: sounding for delaminations, cover depths, corrosion potentials, i_{corr} measurements with both the 3LP and a linear polarization device with a guard ring electrode (Geocisa Gecor Device), and chloride measurements.

A three pound hammer was used for the delamination survey. By placing a hand on the slab and tapping around it with the hammer one can accurately locate delaminations by detecting the differences in vibration.

Cover depths were measured using a Proceq Profometer 3. The device has a manufacturers reported accuracy of ± 0.1 inch.

The potential survey was conducted in accordance with ASTM-876-87. Prior to the potential survey, the slab was sprayed with water and allowed to surface dry to improve conduction.

i_{corr} measurements were first taken with the Gecor Corrosion Rate Device to minimize over-polarization of the rebar test sites. The measurement procedure is presented in Appendix B. The Gecor device, a linear polarization device, employs 2 counter electrodes, the central counter electrode which provides the polarization current and the guard ring electrode which provides a confining current to limit the area of polarization.

The device employs 3 reference electrodes. The reference electrodes are solid Ag-AgCl cells which rely on the Cl⁻ ions found in the tap water used to saturate the contact sponge. Since the Cl⁻ ion content of tap water is quite small and variable depending on location, the measurements of E_{corr} are not comparable to those taken with a standard electrode [49].

One of the reference electrodes is located at the center of the central counter electrode and measures ΔE_{corr} during polarization. The other 2 cells are used to adjust the magnitude of the confinement current applied by the guard ring.

The device determines i_{corr} using the Stern-Geary Equation (Equation 7). The Tafel Slope constant B is equal to 26 mV. R_p is calculated as follows:

$$R_p = A \left(\frac{\Delta E}{I_0} - R_s \right) \quad (11)$$

where,

A = Surface area of the reinforcement steel bounded by the guard ring electrode, A=132.7 cm

ΔE = change in the equilibrium potential measured by the central reference electrode

I₀ = Intensity of current applied by the central counter electrode

R_s = Ohmic resistance of the concrete between the reference electrode and the rebar as measured by a positive feedback from the potentiostat

The measurements were taken on all the transverse bars across the slab before a second measurement was taken at a different location on a single transverse bar. The 3LP measurements were taken at least 1 hour after the Gecor measurement, following the procedure described previously (Section 3.3.2).

Chloride measurements were taken at 2 locations on each slab as described previously (Section 3.3.3)

3.8.2 Removal of Chloride Contaminated Concrete

Prior to the application of the corrosion inhibitors the cover concrete was removed to the top layer of reinforcing steel. In order to obtain the same surface texture found on a bridge deck milled in the field, a commercial milling machine and crew was provided by Lanford Brothers Construction.

Unfortunately, the slabs could not be properly anchored to allow accurate milling. To avoid damaging the slabs, the remainder of the cover concrete was removed by sawing the slab with a walk-behind concrete saw using a 3/16" thick diamond blade. The sawed concrete was removed with an electric demolition hammer.

3.8.3 Application of Corrosion Inhibitors

The surface ponding technique used for the small scale

specimens would be difficult and expensive under field conditions. Therefore, the surface applied corrosion inhibitors were sprayed on the slabs using a ½ gallon polyethylene garden sprayer. Three equal spray applications were applied to the slab, the second application was applied ½ hour and the third 12 hours after the initial spraying. The spraying rates for a single application are shown in Table 4.

Table 4. Spray Application Rates

Surface Applied Inhibitor	Application Rate (ft ² /gal.)
Alox 901	70
Cortec VCI-1337	225
DCI (Calcium Nitrite)	150

The application rates were determined by spraying the surface until it appeared to be uniformly saturated, and then dividing the area of the slab by the volume of inhibitor used.

Sodium tetraborate was not used in the Phase II study because it did not perform as well as the LMC controls where the cover concrete was removed.

3.8.4 Surface Preparation

After the inhibitors had dried, the surface of the slab

was blasted clean of loose particles with compressed air. The slabs which were treated with Alox 901 and Cortec VCI-1337 were lightly sandblasted to remove residues left by the inhibitors in order to achieve an acceptable bond strength.

3.8.5 Placement of Slab Overlays

Forms were constructed for the slabs primarily with $\frac{5}{8}$ " BC Grade exterior plywood. The forms were fasten with steel angles, drywall screws and duplex nails. The slabs were placed in the form with a forklift such that the ends of the transverse bars on one side would be accessible after the overlay was placed. This allowed accurate location of the steel after overlay, and easy connection to the rebar (working electrode).

Mix designs and batch characteristics are provided in Appendix A, Tables A-11 through A-13. The concrete for the slab overlays was mixed in the same manner as the small scale specimens (Section 3.5.5). Exceptions to this procedure are discussed below.

Due to the volume of concrete necessary for the slabs, only 3 cylinders were cast for compressive strength measurement. One cylinder from each batch was tested at 7 days. The remaining pairs were tested at 28 days. Two beams $15\frac{3}{4}$ "x3"x4", were cast from each mix design for rapid freeze-thaw testing.

The plastic overlay concrete was consolidated with a vibratory probe. The surface was screeded with a vibratory screed prior to finishing.

After finishing the slabs were covered with moist burlap and polyethylene sheeting and allowed to cure for 3 days. The forms were removed after 7 days and the sides of the slab coated with SURE-POXY LMLV epoxy. The location of the top layer of reinforcement steel was marked on the surface with a permanent marker. The end of a transverse bar was tapped for a lead wire. The surface moist slabs were stored indoors and covered with plastic sheeting.

3.9 Concrete Resistance to Rapid Freeze-Thaw Cycles

The concrete beams cast with the slab overlays (Section 3.8.5) were tested in accordance with ASTM C666-84 Procedure A, "Resistance of Concrete to Rapid Freezing and Thawing." The durability factor for the concrete was determined by measuring the reduction in the fundamental transverse resonant frequency. The resonant frequency was measured using Grindo-Sonic MK4x Instrument.

Chapter 4.0 Results and Discussion

There were three major objectives of this investigation:

1. Estimating the effectiveness of corrosion inhibitors applied to corroding reinforced concrete, for which the chloride contaminated cover concrete has been removed, in a manner practical for field use.
2. Determining the effect of the inhibitors on the durability of concrete overlay systems.
3. Preparation of application specifications for field use, including an estimate of the increased service life.

4.1 Pre-treatment Corrosion Rate Measurements

A specimen identification code was developed for the small scale specimens based on the specimen configuration, initial corrosion activity, and the applied treatment. For example,

code: 1H-D1-DCI

1H → A specimen containing one triad of reinforcing steel, with a high initial corrosion rate as defined by Table 1.

D1 → The specimen was dried to 180° F. at a depth of $\frac{1}{2}$ " below the reinforcing steel, and ponded with the

corrosion inhibitor for 1 day.

DCI → The corrosion inhibitor applied to the specimen according to Table 3.

The only exception to this system are the control overlay specimens shown in Table 5 below.

Table 5. Control Overlay Specimen Identification Codes.

Specimen	Treatment
2M-LMC	1" LMC overlay with the Cl ⁻ contaminated cover concrete left in place
2L-BC	2½" Bituminous Concrete Overlay with a waterproof membrane, Cl ⁻ contaminated cover concrete left in place
2L-TP	Thin Polymer Overlay, Cl ⁻ contaminated cover concrete left in place
2M-CON	Untreated Control

The specimen codes will be used to identify the treatments throughout the remainder of the text.

The pre-treatment i_{corr} and E_{corr} values, and Cl⁻ concentrations at the bar level for the specimens immediately prior to treatment are shown in Table 6. The Cl⁻ content as a function of depth is presented in the Appendix C, Table C-4. Since both E_{corr} and the Cl⁻ ion

Table 6. Average pre-treatment corrosion current, potential, and chloride ion content at the level of the reinforcing steel for all treated specimens.

Specimen	i_{corr} (mA/ft ²)	E_{corr} CSE (-mV)	Cl ⁻ Ion (lbs/yd ³)
1H-D1-DCI	9.78	476	28.8
1H-D1-SB	12.84	445	26.1
1H-D1-AX	37.48	491	27.3
1H-D1-COR	9.93	489	23.8
1H-D1-LMC	9.72	473	24.7
2ML-1-DCI	1.91	246	2.0
2ML-1-SB	2.34	298	1.6
2ML-1-AX	1.50	303	2.3
2ML-1-COR	1.21	200	1.6
2ML-2-DCI	2.04	294	1.8
2ML-2-SB	0.93	258	1.5
2ML-2-AX	2.53	376	2.0
2ML-2-COR	1.20	213	1.2
2ML-0-LMC	1.31	310	2.3
2M-LMC	2.95	390	2.6
2L-BC	1.63	280	1.4
2L-TP	.94	261	1.8

Continued.

Table 6. Continued.

Specimen	i_{corr} (mA/ft ²)	E_{corr} CSE (-mV)	Cl ⁻ Ion (lbs/yd ³)
1M-1-DCI	4.86	565	12.8
1M-1-SB	4.92	536	14.3
1M-1-AX	4.96	567	16.6
1M-1-COR	5.64	531	13.1
1M-0-LMC	7.32	567	16.8
1M-CON	8.90	534	15.5
1ML-D1-DCI	0.98	404	4.1
1ML-D1-SB	1.24	363	1.9
1ML-D1-AX	1.28	407	1.1
1ML-D1-COR	1.27	430	2.4
1ML-D0-LMC	1.00	388	2.1
1L-D1-DCI	0.30	275	3.6
1L-D1-SB	0.27	172	0.6
1L-D1-AX	0.42	272	1.3
1L-D1-COR	0.36	275	5.8
1L-D0-LMC	0.31	172	1.8
1L-1AX-DCI	0.78	388	1.3
1L-1AX-COR	0.51	325	3.8
1H-1AX-LMC	6.72	564	15.1

concentration represent driving potentials for the corrosion reaction, an effort was made to determine if they correlated with the corrosion rates using MINITAB Statistical Software. A simple linear regression was performed using E_{corr} and the Cl^- ion concentration as predictor variables for the corrosion rate. The predictor variables are the independent or x variables, in this case i_{corr} is the dependent or y variable. MINITAB calculates both the best-fit linear equation ($y = aX + b$) and the coefficient of determination (r^2) which represents the degree of correlation between the variables or the fraction of variation in y explained by the fitted equation [50]. MINITAB also calculates the standard error of estimate (s).

The r^2 value for E_{corr} as the predictor variable on the dependent variable i_{corr} was 24.8%, $r^2(\text{adj})$ was 22.6%, $s = 5.844$ and the number of observations (n) = 36. This indicates a small degree of correlation. However, the standardized residual for the data representing specimen 1H-D1-AX was 5.30, a value almost 5 times higher than those calculated for the other specimens.

The standardized residual is the difference between the predicted and observed values divided by the standard deviation of all the residuals. Thus, a standardized residual several times greater than those for the remainder

of the observations may indicate an outlier. An outlier is an observation which is significantly different from the majority of the data. To better explain the response of the majority of the data an outlier can be removed from the data set.

Based on the standardized residual, and the extremely high initial corrosion rate for specimen 1H-D1-AX, the data representing the specimen was removed from the data set. One explanation for the unusually high i_{corr} reading may be the presence of a micro-crack in the concrete above the bar at the time the reading was taken. The micro-crack would have allowed a direct circuit to form between the counter and working (rebar) electrodes which would account for the unusually high i_{corr} reading. Based on 35 observations, the r^2 for the model with the data for 1H-D1-AX removed, was 50.5%, $r^2(\text{adj})$ was 49.0% and $s = 2.472$ indicating a better correlation, but not high enough to use E_{corr} as a predictor for the corrosion rate.

An effort was made to confirm the threshold potential above which active corrosion is likely to occur. The data set was randomly divided in half (1H-D1-AX removed) and the regression rerun with E_{corr} as the predictor variable for i_{corr} including an estimation of the 95% confidence and prediction intervals. The r^2 for this model was 48.1%, $r^2(\text{adj})$ was

44.8%, $s = 2.855$ and $n = 17$. All of the data from the other half of the sample set fell within the prediction intervals when the model was cross validated. Using an i_{corr} value of 0.20 mA/ft^2 , for which damage is expected in 10-15 years, as the threshold for active corrosion, the potential as determined from the 95% confidence intervals was -320 mV . For an i_{corr} value 1.00 mA/ft^2 , where damage would be expected in 2-10 years, the threshold potential was -345 mV . This reconfirms the interpretation presented in ASTM C-876-87 (see section 2.4.2, page 18).

Using the Cl^- content as the predictor variable for i_{corr} , the calculated r^2 was 59.1%, $r^2(\text{adj})$ was 57.9%, $s = 4.312$ and $n = 36$. This includes the data representing specimen 1H-D1-AX. A plot of the data including the straight line fit to the data is shown in Figure 5-A. From this plot the large influence of 1H-D1-AX can be seen. Based on the point's standardized residual and i_{corr} reading, it was removed from the data set.

With the data removed for 1H-D1-AX, the calculated r^2 was 90.2%, $r^2(\text{adj})$ was 89.9%, $s = 1.099$ and $n = 35$. This indicates a good correlation between i_{corr} and Cl^- content in lbs/yd^3 as shown in Figure 5-B. The regression equation is:

$$I_{\text{corr}} = 0.422 + 0.385 (\text{Cl}^- \text{ Content}) \quad (13)$$

The author is not suggesting that this relationship is

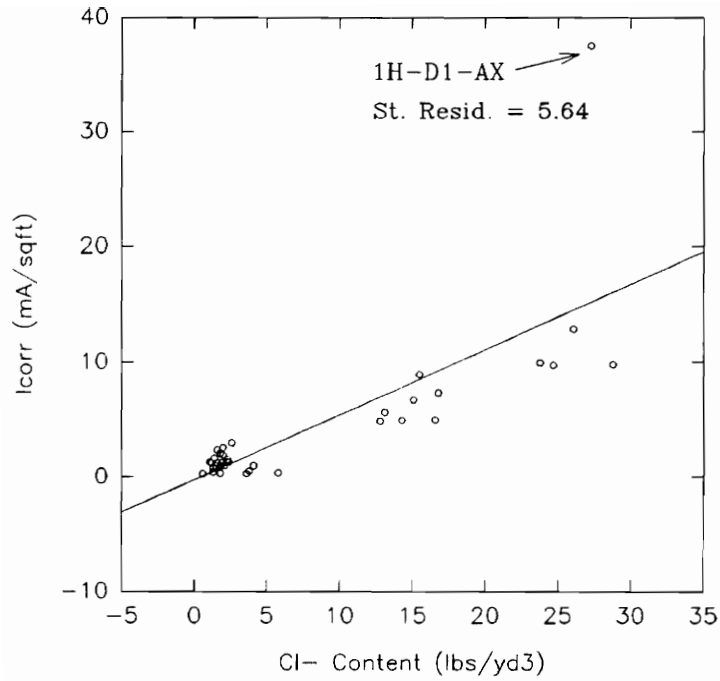


Figure 5-A Icorr vs. Cl- Content
For Complete Data Set

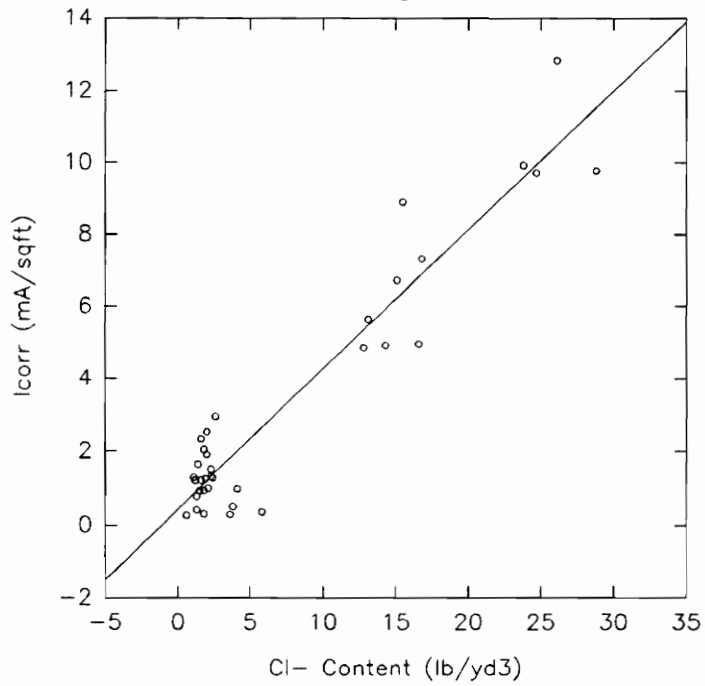


Figure 5-B. Icorr vs. Cl- Content
with 1H-D1-AX Removed

valid for field measurements. However, it is valuable for the laboratory evaluation where the specimens have a known polarization area, and are exposed to a relatively constant relative humidity and temperature.

4.2 Evaluation of Corrosion Inhibitors

Prior to treatment, the specimens were grouped according to their initial corrosion rates. This was done to aid in the comparison of the inhibitors effectiveness. The groups were categorized as low, medium, and high according to the time to expected damage given in Table 2, page 36. In addition, a medium-low category was added for specimens whose i_{corr} rates were in the low end of the 1-10 mA/ft² range for the medium category.

Though some of the initial E_{corr} readings were into the uncertain range, -200 to -350 mV to the CSE, all of the specimens i_{corr} measurements identified them as actively corroding at the time of treatment. The i_{corr} measurements were substantiated by the Cl⁻ ion content being greater than the threshold value with the exception of specimen 1L-D1-SB.

The groups of specimens were treated in three sets over a five month period. By treating the groups of specimens in phases, data from the previous set could be used to determine the best method of application for the successive sets. The first set included four groups:

- 1) The control overlay specimens
- 2) The one-triad, high initial corrosion rate specimens which were dried to 180° F. at a depth of $\frac{1}{2}$ " below the bar level, and ponded for 1 day (1H-1D-***)
- 3) The two-triad, medium-low initial corrosion rate specimens which were ponded for 1 day (2ML-1-***).
- 4) The two-triad, medium-low initial corrosion rate specimens which were ponded for 2 days (2ML-2-***).

The effectiveness of the inhibitor treatment method is based primarily on the i_{corr} measurements obtained from the 3LP. Though the 3LP does not have a guard-ring electrode to confine the area of polarization, the small scale specimens have a known area of corroding steel approximately equal to the 3LP's contact area. E_{corr} measurements are included for comparison. In the case of the two-triad specimens the i_{corr} and E_{corr} measurements shown are the average value for the two top bars.

4.2.1 Control Overlays

The post-treatment i_{corr} and E_{corr} values for the control overlays are shown in Figures 6-A and 6-B. The control overlays represent typical treatment methods used in current practice. One specimen (2L-0-LMC) for which the cover

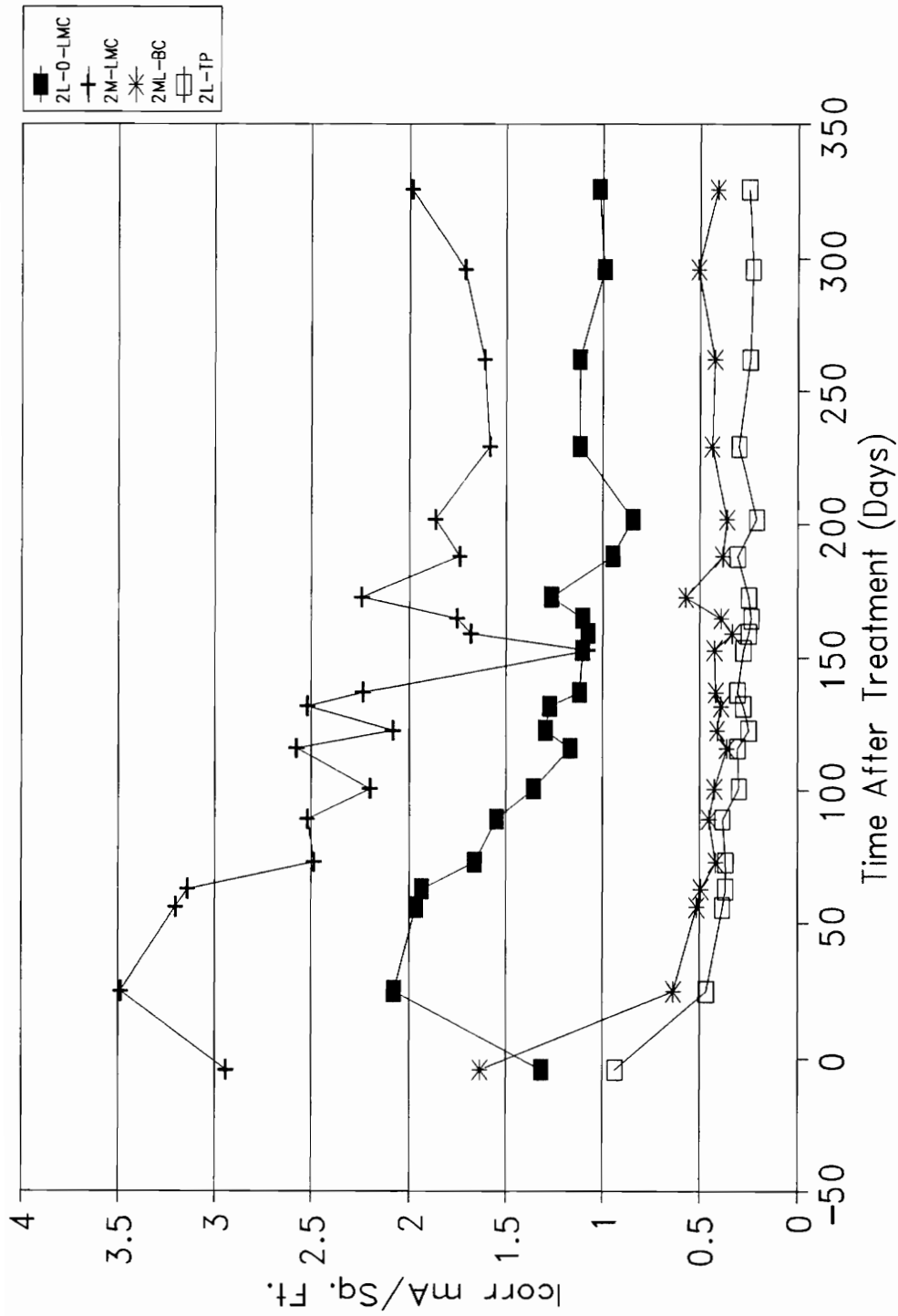


Figure 6 –A. Icorr Readings for Control Overlay, with Low Initial Corrosion Rates

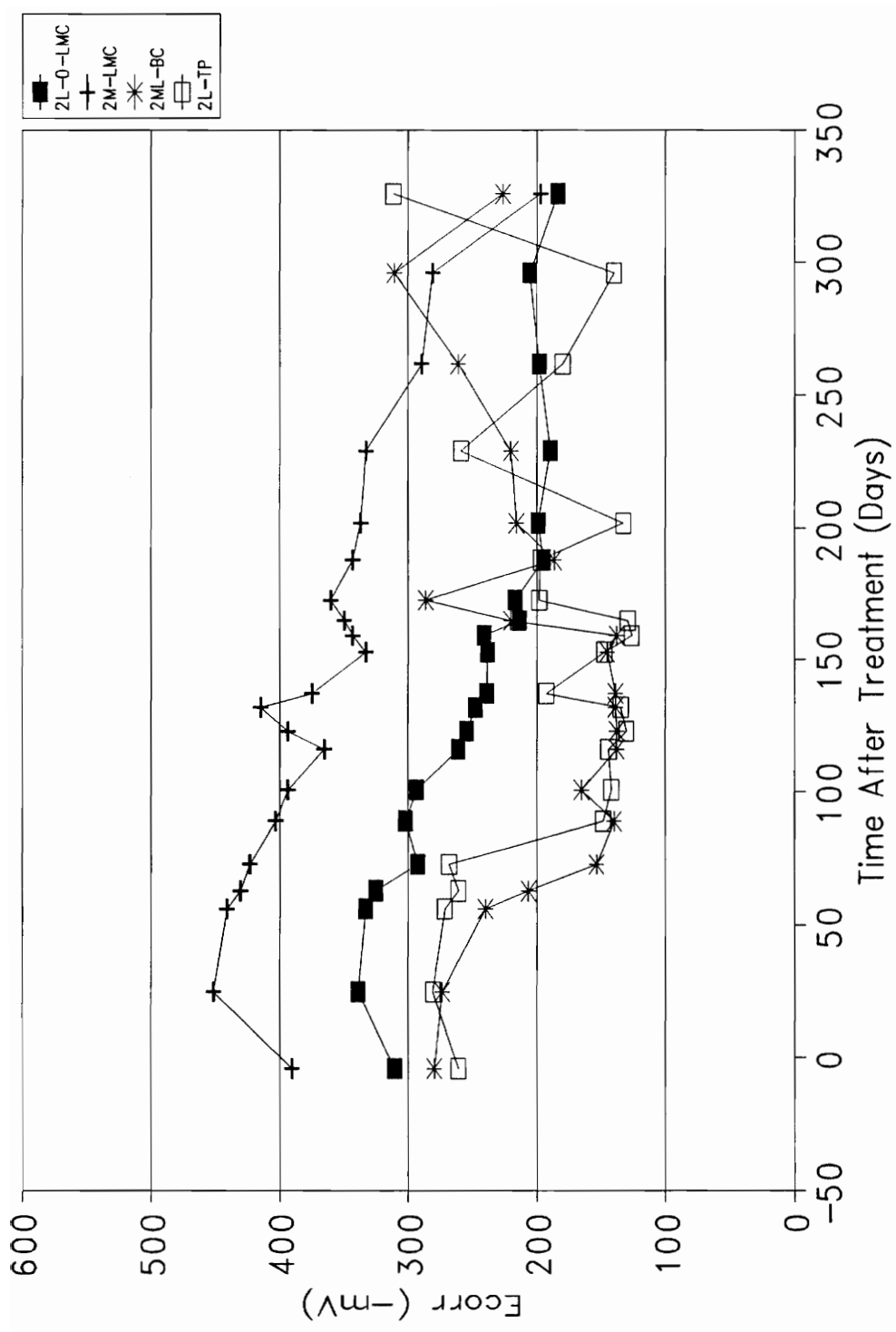


Figure 6-B. Ecorr Readings for Control Overlays with Low Initial Corrosion Rates

concrete was removed prior to overlay is included as a comparison.

Both the 1" LMC overlay (2M-LMC), where the chloride contaminated concrete was left in place, and the 2" LMC overlay where the chloride contaminated concrete was removed to the bar level, (2L-0-LMC), show an increase in i_{corr} immediately after treatment. This is probably due to the increased moisture content in the specimens resulting from the overlays. Measurements taken 63 days after treatment indicate downward trends in the corrosion rates.

In the case of 2M-LMC this is probably due to the specimen drying out as a result of the decreased permeability of the overlay. The decrease in i_{corr} for 2L-0-LMC is probably a combination of the specimen drying out, an increase in the pH around the bar resulting from the fresh concrete, and the migration of chlorides into the overlay decreasing their concentration at the bar level. The E_{corr} readings follow similar trends.

The waterproof membrane installed with the bituminous concrete overlay (2L-BC) and the thin polymer overlay (2L-TP) are both impervious layers which will prevent i_{corr} or E_{corr} measurements from being taken. Therefore, the measurements were taken from the bottom of the specimen with the resistor(s) between the upper and lower mats of steel

disconnected immediately prior to the measurement. The time period between disconnecting the resistor and taking the measurement was probably too short for the test area to reach a new equilibrium which would have excluded the portion of the i_{corr} related to macro-cell corrosion.

Both 2L-BC and 2L-TP exhibit greater than a 50% decrease in corrosion rate after treatment, though neither specimen dropped below 0.2 mA/ft^2 indicating the corrosion had not ceased. The decrease is probably due to a lack of moisture resulting from the impervious overlays. The fluctuation in the E_{corr} measurements may be due to the high resistance of the concrete resulting from the low moisture content.

4.2.2 High Initial i_{corr} , Dried Specimens

Based on the initial i_{corr} readings for these specimens, damage resulting from corrosion was expected in less than two years. The post-treatment performance of the treated specimens is shown in Figures 7-A and 7-B. The LMC control specimen (1H-D0-LMC) displayed a 60% reduction in corrosion rate over a period of 202 days after treatment at which point it remained almost constant at an average i_{corr} of 4.1 mA/ft^2 . The long term reduction in corrosion rate is most likely related to the migration of chlorides into the

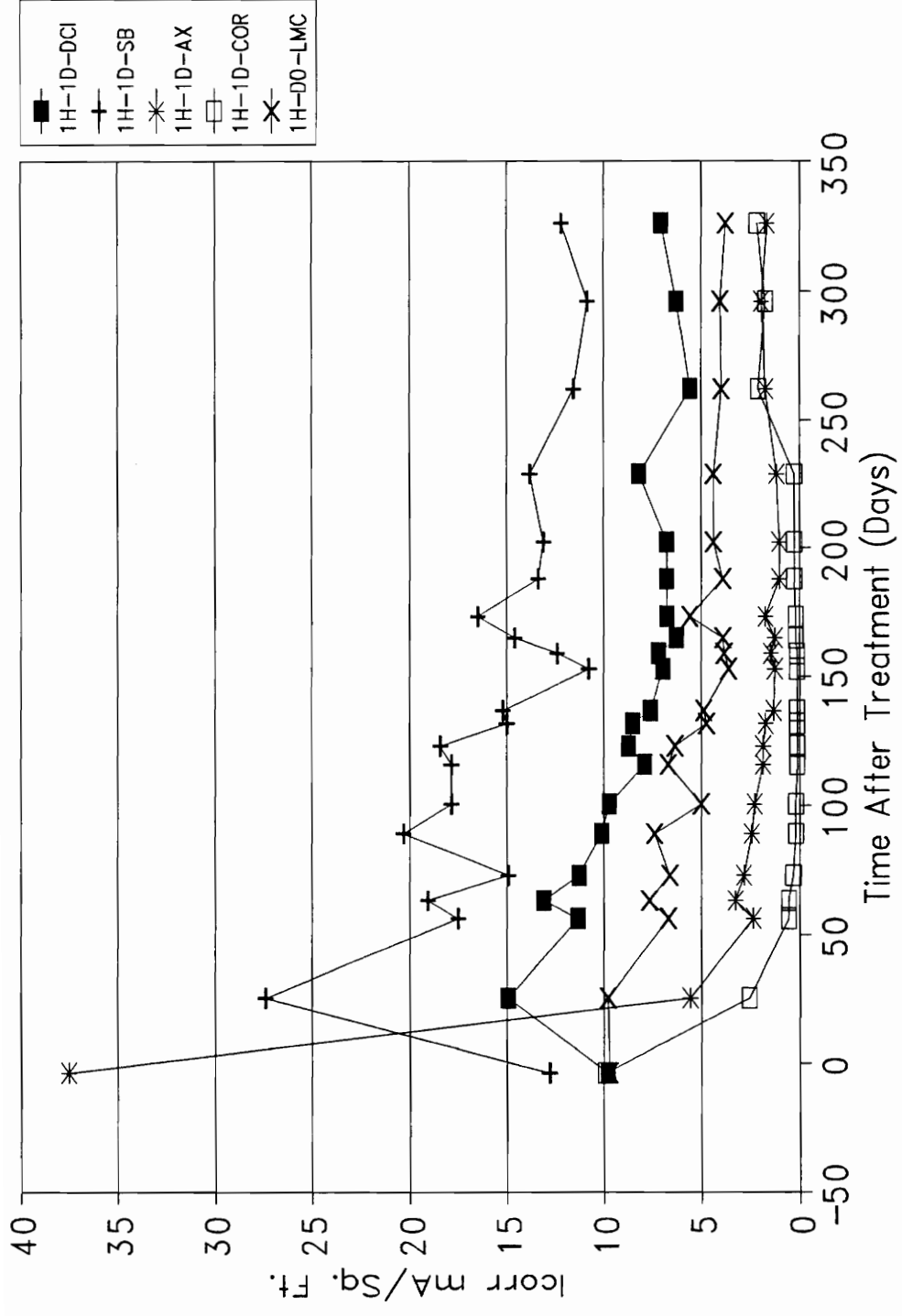


Figure 7-A. Icorr Readings for Dried Specimens with High Initial Corrosion Rates

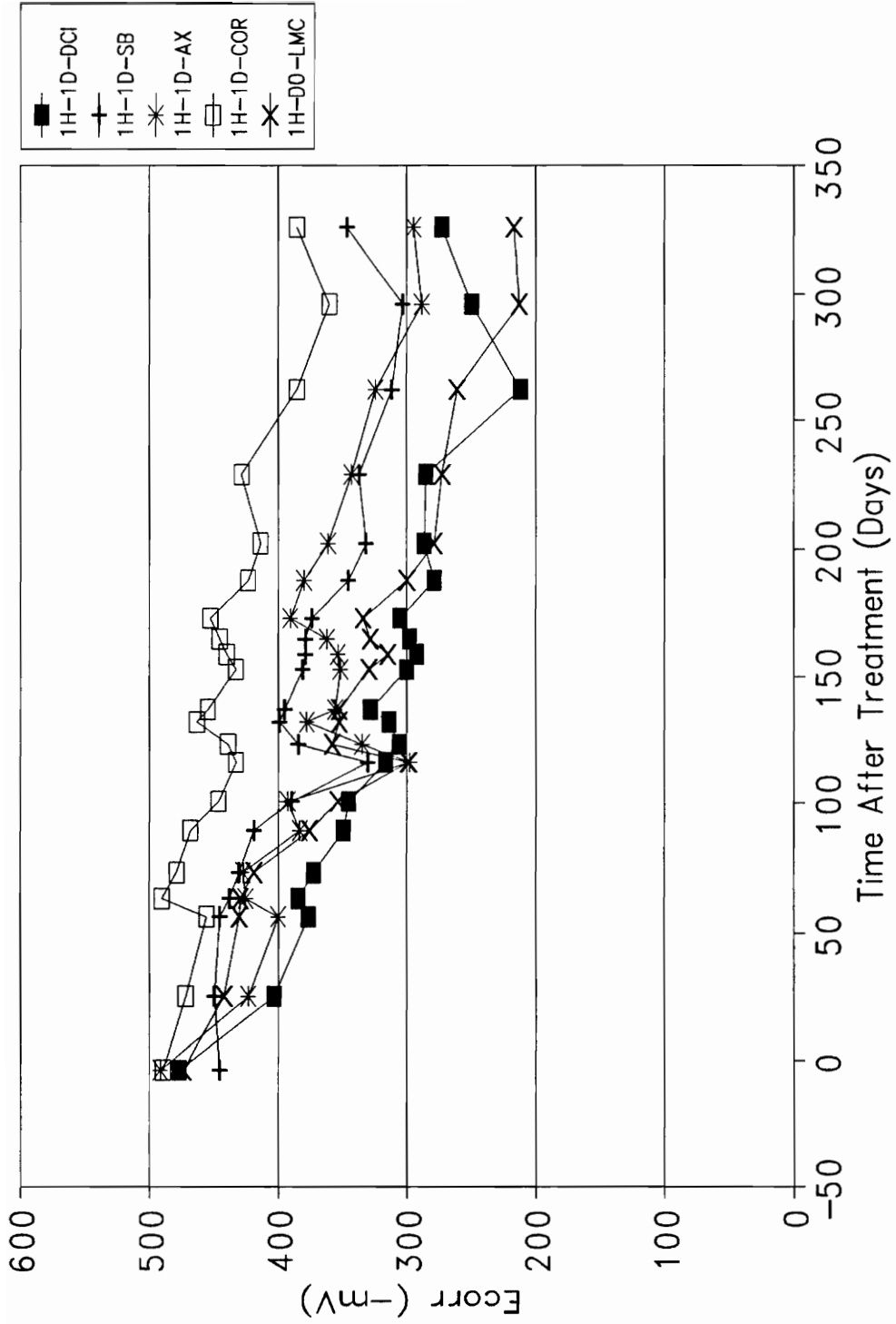


Figure 7 -B. Ecorr Readings for Dried Specimens with High Initial Corrosion Rates

uncontaminated overlay concrete. The increase in the pH of concrete surrounding the rebar and a possible decrease in the rate of diffusion of water and oxygen may also have contributed to the reduction.

The specimens treated with Alox and Cortec showed dramatic decreases in corrosion rate immediately after treatment. Since the control specimen did not decrease as rapidly, this decrease must be the result of the reaction of the corrosion inhibitors with the corrosion cells.

The initial decrease of the Alox treated specimen (1H-D1-AX) may be somewhat misleading based on the previous discussion of its initial corrosion rate. However, even if the predicted value of i_{corr} (10.93 mA/ft^2) based on the specimens Cl^- content is used, the treatment still showed a significant decrease.

More importantly, sufficient quantities of the inhibitor seemed to have been absorbed into the specimen, as a result of drying, to form a stable metal soap layer on the rebar. This layer reduced metal dissolution such that the average i_{corr} reading from 56 to 326 days after treatment is 1.8 mA/ft^2 . This represents an 80% decrease in corrosion rate.

However, it is also possible that the inhibitor seeped into a micro-crack surrounding the rebar as discussed in

Section 4.1. This may have allowed greater quantities of the inhibitor to react with the rebar than normally possible.

Corrosion activity in specimen (1H-D1-COR), which was treated with Cortec, ceased based on its corrosion rate ($<0.20 \text{ mA/ft}^2$), for the period between 56 and 229 days after treatment. The initial application of Cortec 1337 was apparently sufficient to form a monolayer over the majority of the corrosion sites, stopping corrosion. After 229 days, it appears that the gaseous diffusion of the inhibitor from the overlay was not sufficient to maintain a complete monolayer and the i_{corr} readings increased slightly.

The specimens treated with DCI and sodium borate (1H-D1-DCI and 1H-D1-SB) showed increases in corrosion rate immediately after treatment. Though 1H-D1-SB demonstrates a decreasing trend after the initial increase, only one reading taken 153 days after treatment, is less than the initial i_{corr} . The author's examination of data collected by Webster et al [51] in a preliminary study suggests that the effectiveness of sodium borate is pH dependent. The pH of chloride contaminated concrete may not be sufficiently high for it to act as an effective inhibitor.

The specimen treated with DCI (1H-D1-DCI) shows a relatively consistent decrease in i_{corr} after its initial

increase until 159 days after treatment, at this point it appears to be stabilizing around 6.8 mA/ft². The E_{corr} measurements show a fairly consistent increase until 262 days after treatment after which they became more negative.

Overall, DCI did not perform as well as the control specimen. The ineffectiveness of DCI may be due to the short ponding period or the low concentration of calcium nitrite used for ponding.

An effort was made to estimate the Cl⁻/NO₂⁻ ratio at the bar level. The Cl⁻ content was 28.8 lbs/yd³ immediately prior to treatment. Previous research conducted by Dutta [52], found mortar cubes dried to 175° F to have a 9.7% by volume absorption of monomer. From this absorption percentage it was estimated that the nitrite content at the bar level was 1.9 lbs/yd³, resulting from the application of a 0.1 M calcium nitrite solution as presented in Equation 14.

$$A_v \times 27 \frac{ft^3}{yd} \times 7.48 \frac{gal}{ft^3} \times U_{wi} \frac{lbs}{gal} \times I_{con} \times \frac{91.9}{132} = NO_2^- \frac{lbs}{yd^3} \quad (14)$$

where,

A_v = % absorption of the concrete by volume expressed as a decimal.

U_{wi} = Unit weight of the inhibitor, 8.5 lbs/gal

I_{con} = Inhibitor concentration % by weight, expressed as a decimal, 0.1 M = 1.32% calcium nitrite

91.9/132 = Molecular ratio of nitrite to calcium
nitrite

Research conducted by Berke et al [44], concluded that for inhibition to occur, the chloride:nitrite ratio must be less than 2. For this specimen the estimated chloride nitrite ratio was 15.

4.2.3 Medium-Low Initial i_{corr} , One Day Ponding

The i_{corr} and E_{corr} measurements for the specimens with medium-low initial corrosion rates which were treated with a one day ponding application and inhibitor modified overlay are shown in Figures 8-A and 8-B. Though the initial corrosion rates were somewhat divergent, the group displays similar trends to the previous group. Though all of the treatments demonstrated a reduction in i_{corr} , The specimen treated with Alox (2ML-1-AX) showed the most significant improvement.

The mean i_{corr} for the Alox treatment was 0.097 mA/ft² from 89 days after treatment till the end of the survey. The corresponding E_{corr} approached 200 mV. These measurements indicate the cessation of corrosion activity in the specimen. The improved performance of Alox in relation to the other inhibitors maybe due to its carrier solvent, alcohol. The alcohol may displace some of the capillary water allowing more of the inhibitor to be absorbed. This effect would not have been noticeable in the dried

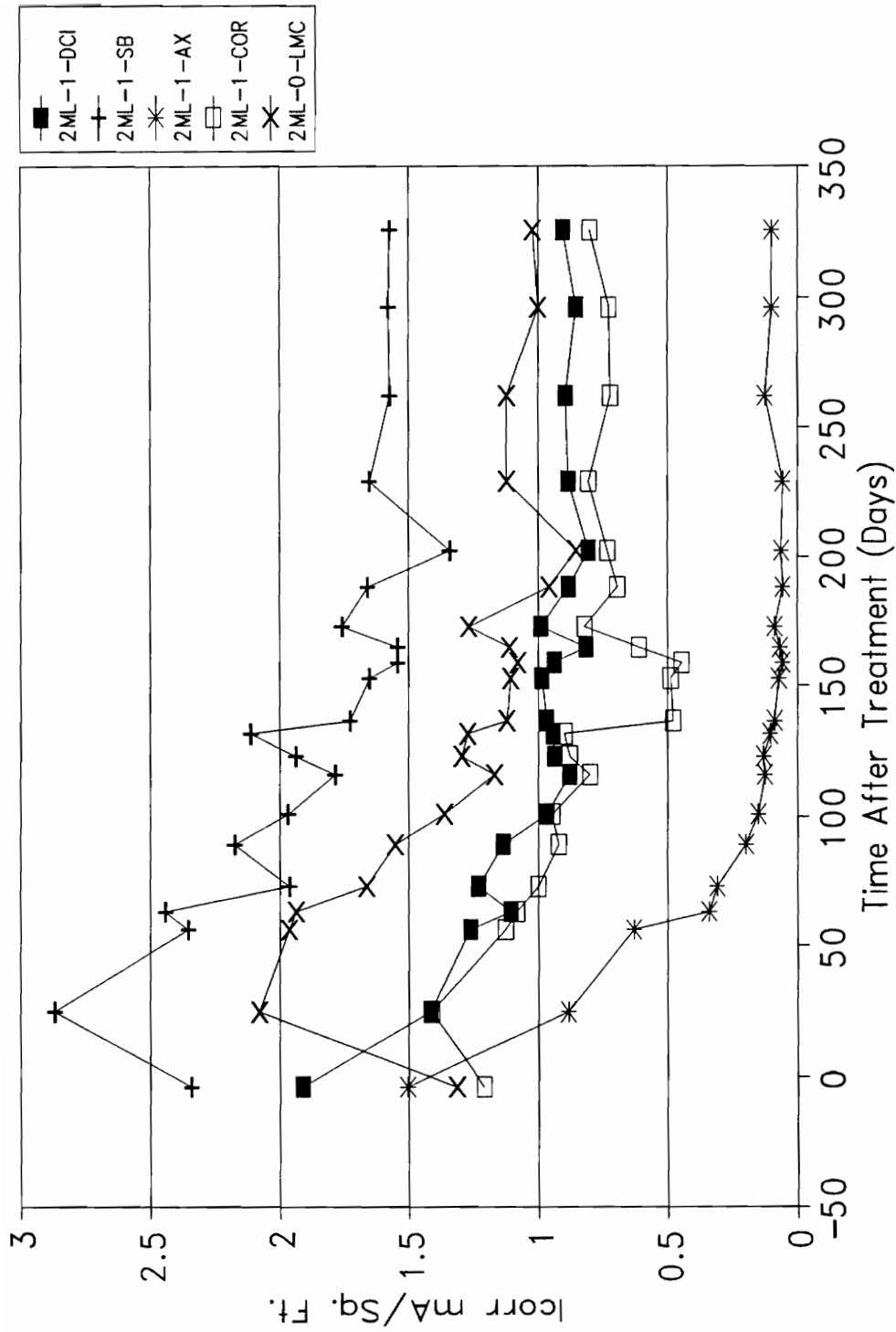


Figure 8-A. Icorr Readings for 1 Day Ponding Specimens with Medium -Low Initial Corrosion Rates

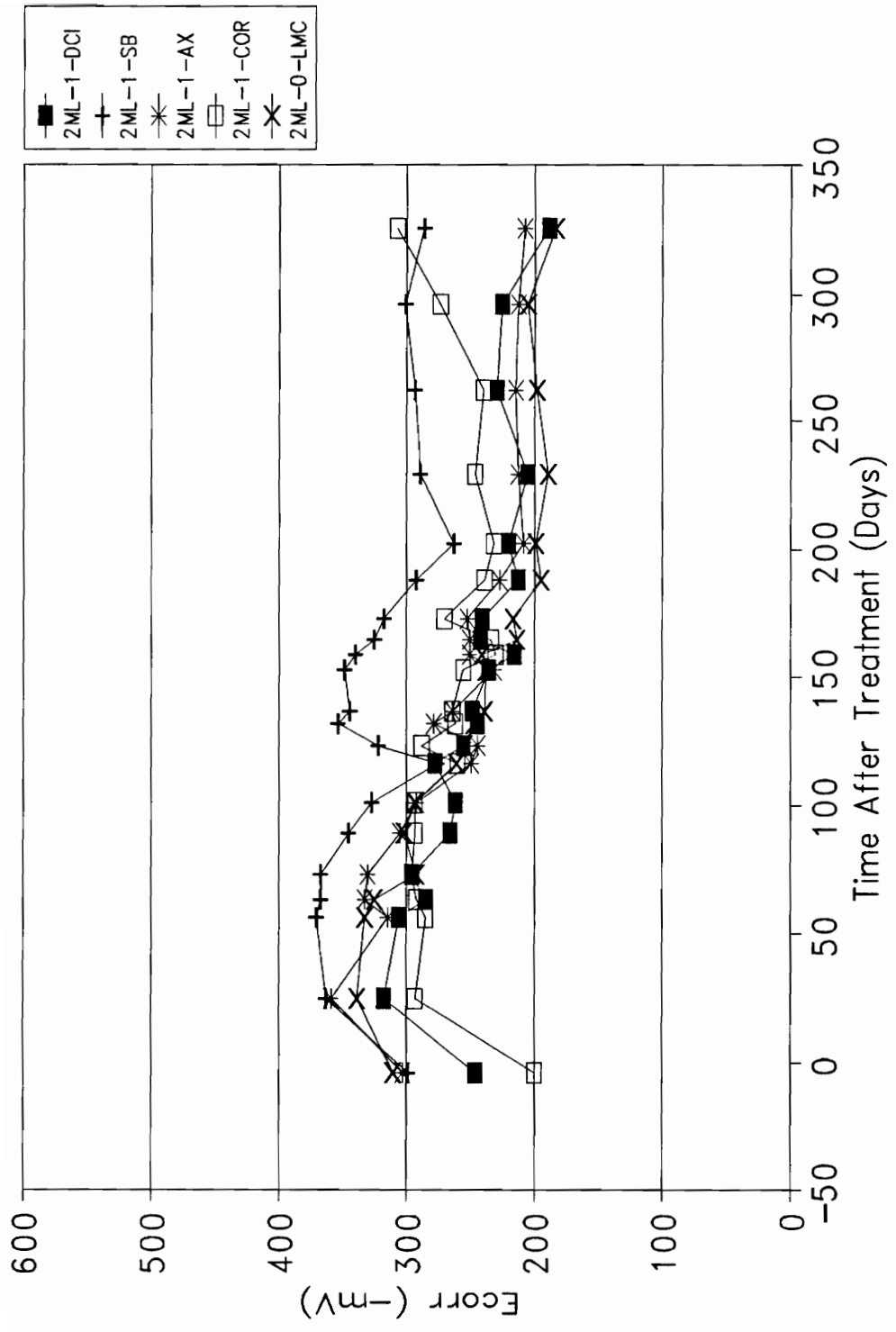


Figure 8-B. Ecorr Readings for 1 Day Ponding with Medium-Low Initial Corrosion Rates

specimens.

The specimens treated with Cortec (2ML-1-COR), DCI (2ML-1-DCI), and the LMC control (2ML-0-LMC) performed almost identically. The specimen treated with DCI had the best numeric improvement, stabilizing approximately 1 mA/ft² below its pretreatment corrosion rate. The improved performance of DCI is probably related to the relatively low initial chloride content (2.0 lbs/yd³). Thus, requiring a lower concentration of calcium nitrite to compete with the Cl⁻ ions for the Fe⁺⁺ ions in order to form a protective layer. Additionally, the initial drop in i_{corr} suggests an inhibitive action since the specimen does not demonstrate the same initial increase as the control.

The chloride:nitrite ratio was estimated in an effort to confirm this theory. Concrete will lose ½% to 3% by weight of evaporable water if it is maintained at a relative humidity of 50% [53]. Using a 3% water loss in air drying, and assuming re-saturation of the exposed concrete at the bar level with a 0.1 M calcium nitrite solution, a nitrite concentration of 1.1 lbs/yd³ can be estimated using Equation 15:

$$A_w \times W_c \times 27 \frac{ft^3}{yd} \times I_{con} \times \frac{91.9}{132} = NO_2^- \frac{lbs}{yd^3} \quad (15)$$

where,

A_w = % absorption of the concrete by weight expressed as a decimal.

W_c = Unit weight of the concrete, 145 lbs/ft³

I_{con} = Inhibitor concentration % by weight, expressed as a decimal, 0.1 M = 1.32% calcium nitrite

91.9/132 = Molecular ratio of nitrite to calcium nitrite

The corresponding chloride:nitrite ratio based on this estimation is 1.8. This indicates sufficient nitrite content to control corrosion as cited in Section 4.2.2.

The performance of the Cortec treatment was only fair. Both the corrosion rate and potential show an upward trend toward the end of the monitoring period.

The sodium borate treatment also seems somewhat effective in this case. The specimen stabilized at 1.57 mA/ft², an improvement of 0.77 mA/ft² over its pre-treatment corrosion rate. However, this reduction was not sufficient to move it into the next lowest category for time to expected damage.

4.2.4 Medium-Low Initial i_{corr} , 2 Day Ponding

The progression of post-treatment i_{corr} and E_{corr} group of measurements for the medium-low initial i_{corr} , 2 day inhibitor ponding group is shown in Figures 9-A and 9-B. A comparison of the overall performance of this group with the previous

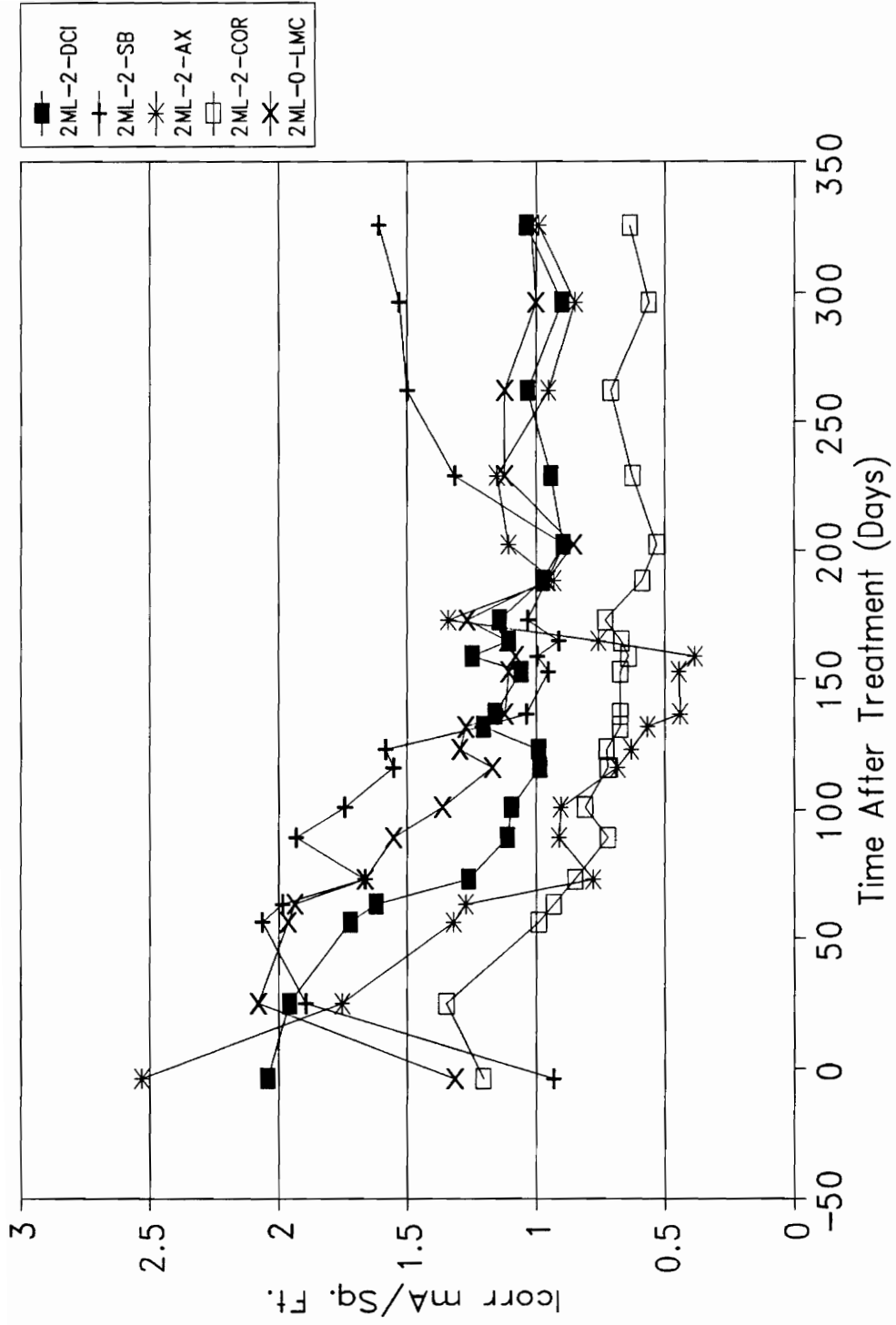


Figure 9—A. Icorr Readings for 2 Day Ponding Specimens with Medium—Low Initial Corrosion Rates

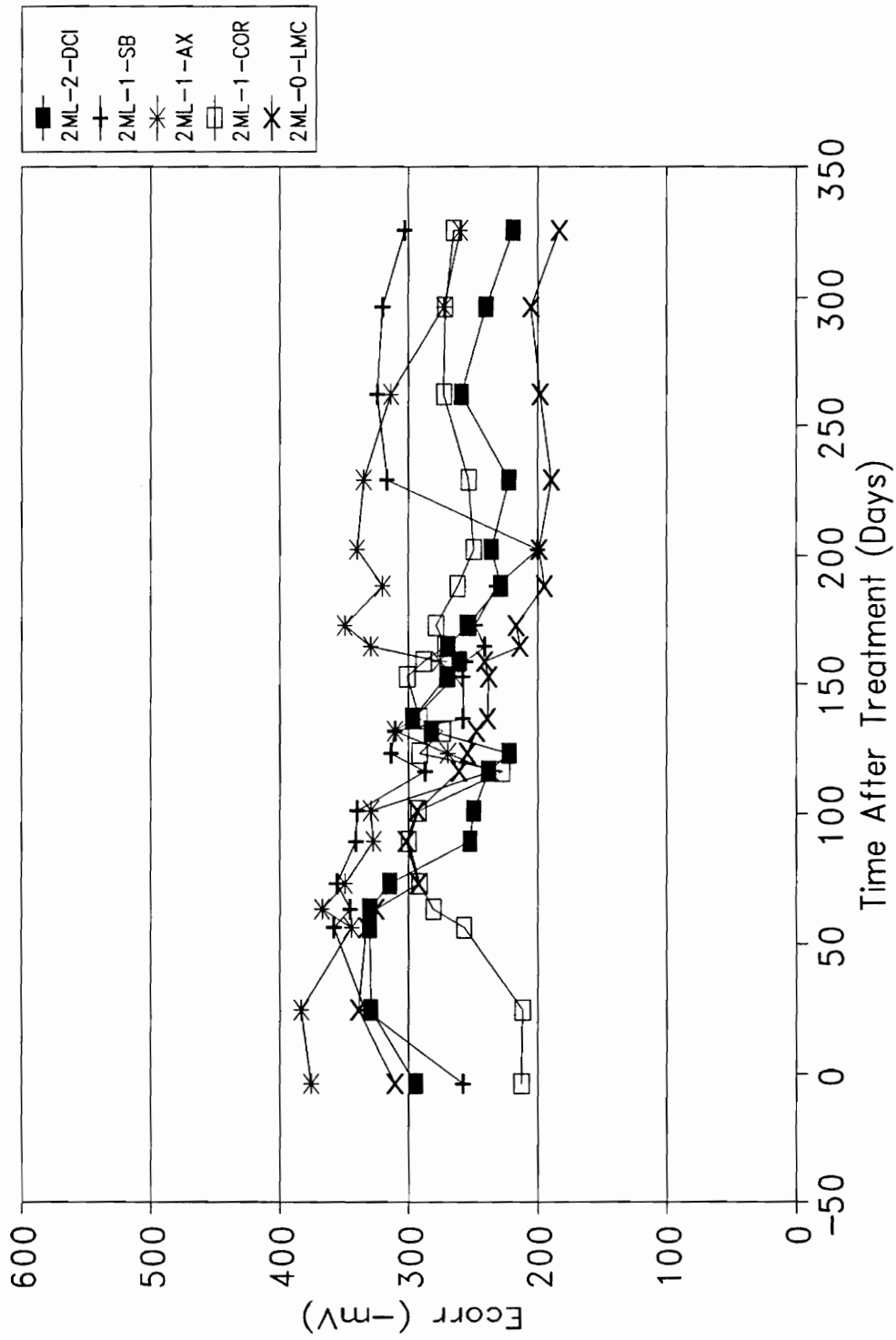


Figure 9-B. Ecorr Readings for 2 Day Ponding Specimens with Medium-Low Initial Corrosion Rates

group, which was ponded for only 1 day, indicates no significant reduction in corrosion rate. Since neither specimen was dried, the capillaries were probably filled with water, allowing a finite amount of absorption independent of the ponding time. Based on these observations additional treatments utilizing a 2 day ponding period were terminated.

The specimen treated with Alox displayed the greatest decrease in corrosion rate until 159 days after treatment when it experienced an abrupt increase in i_{corr} and E_{corr} . The increase is probably due to a failure of some portion of the metal soap layer.

The author suspects that since the remainder of the rebar was largely passive, the area where the failure occurred experienced accelerated corrosion as a result of the high anode to cathode ratio. However, sufficient quantities of the inhibitor were apparently present to allow a partial healing of the layer. Overall, this may be an example of the reaction caused by a dangerous inhibitor.

The specimen treated with sodium borate also displayed a performance unlike the previous group. In this case the inhibitor seems to have been completely ineffective. The final i_{corr} reading was 73% higher than the pre-treatment measurement, even though the Cl^- ion content was lower than

that in the previous group.

In all three of the treatment groups examined thus far, the control overlay has had the most noble final E_{corr} measurement. This may be due to the fact that the inhibitors block the corrosion process while in the case of the control the reduction in corrosion rate is most likely due a decrease in the Cl^- ion concentration.

4.2.5 Medium Initial i_{corr} , 1 Day Ponding

The post-treatment data for the specimens with medium initial i_{corr} rates which were exposed to surface applied inhibitors for 1 day are shown in Figures 10-A and 10-B. These specimens were included in the second treatment set.

An untreated control specimen (1M-CON) with the chloride contaminated cover concrete left in place was included in this group of specimens. The decrease in corrosion rate shown 50 days after treatment of the other specimens is due to the temporary removal of the specimen from the 6% NaCl ponding cycle which allowed the specimen to dry out. The specimen was used to demonstrate corrosion rate measurement devices at an AASHTO convention during this time period. A crack was produced in the specimen from the expanding corrosion products, 99 days after the treatment of the other specimens. A corrosion rate of 15.0 mA/ft^2 was measured at this time.

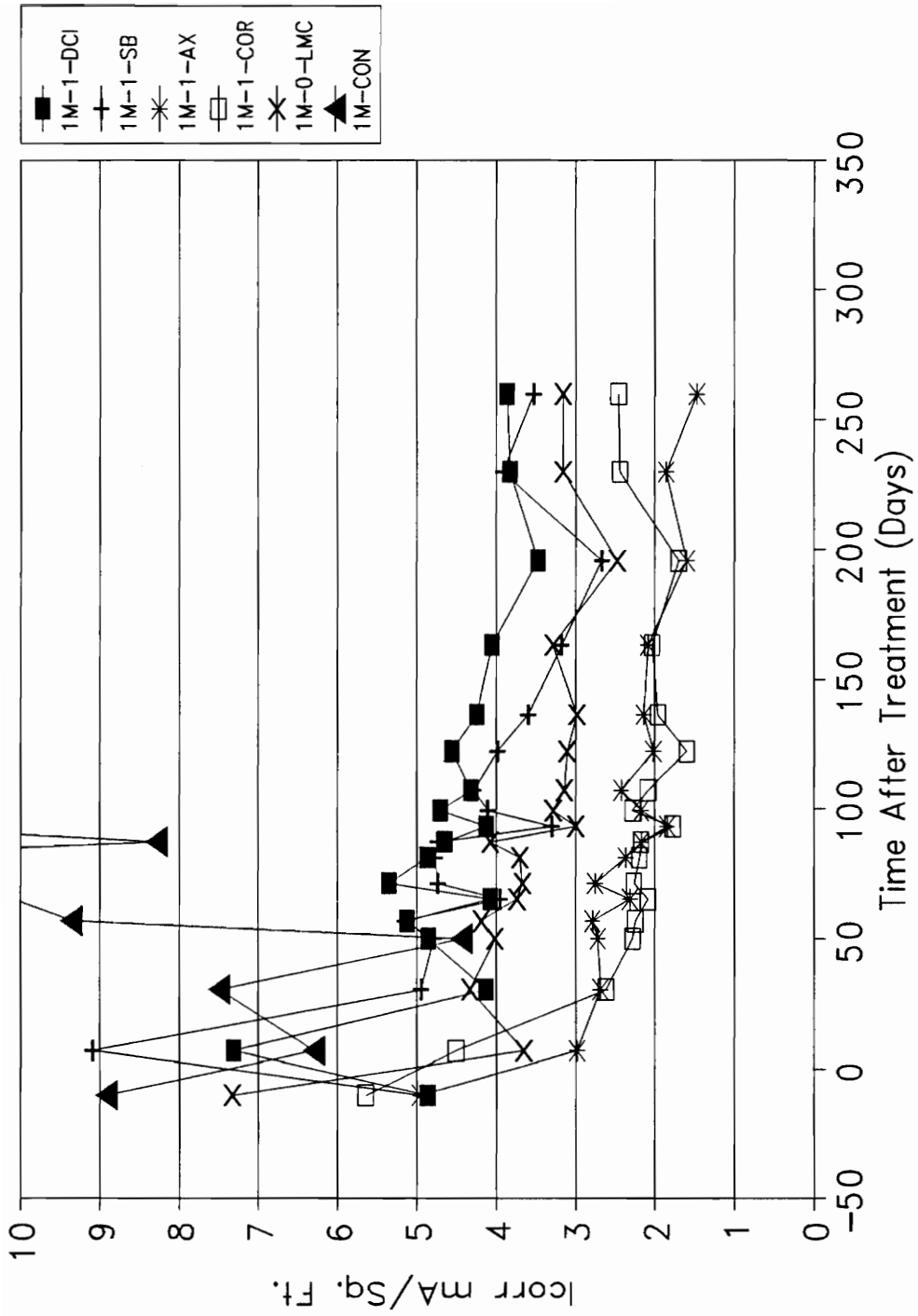


Figure 10-A. Icorr Readings for 1 Day Ponding Specimens with Medium Initial Corrosion Rates

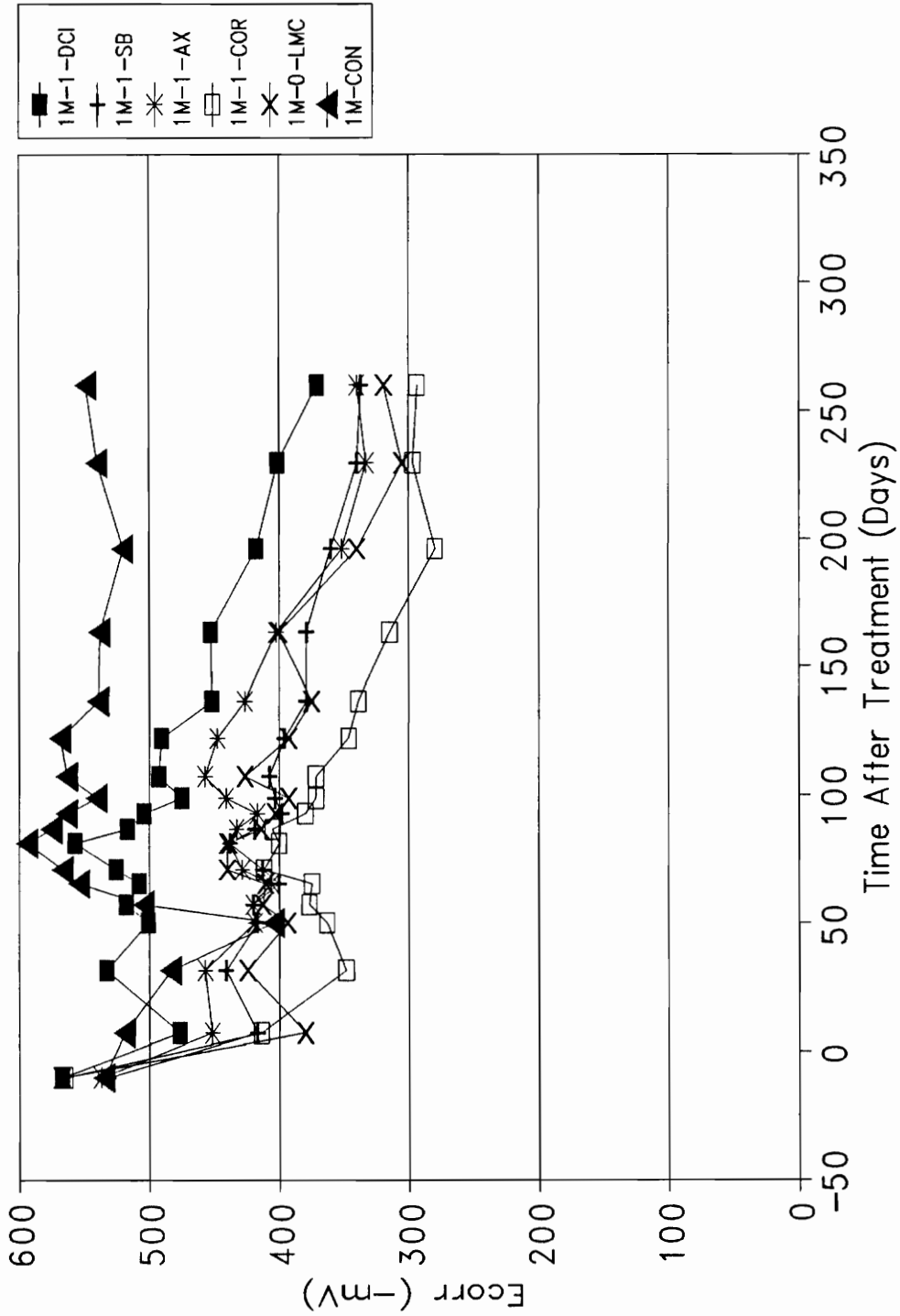


Figure 10-B. Ecorr Readings for 1 Day Ponding Specimens with Medium Initial Corrosion Rates

All of the specimens, for which the chloride contaminated cover concrete was removed, showed improvement after treatment. The specimens treated with Alox and Cortec performed almost identically, tending to fluctuate around a corrosion rate of 2.0 mA/ft² from 59 days after treatment till the conclusion of the investigation. This represents approximately a 60% decrease in i_{corr} . The LMC overlay, without any inhibitors, showed a 57% decrease in i_{corr} by the end of the monitoring period.

The specimens treated with DCI and Sodium Borate each improved by about 1 mA/ft² after treatment. However, this improvement is less than the controls. The E_{corr} measurements for the DCI treatment did improve, and were more noble than the LMC control. Though this increase has been relatively consistent throughout the treatment groups, the author can offer no explanation based on the mechanism of inhibition described by the manufacturer.

4.2.6 Medium-Low Initial i_{corr} , Dried Specimens

The post-treatment progression of i_{corr} and E_{corr} readings for the group of specimens with medium-low initial corrosion rates which were dried to 180° F. at a depth of ½" below the bar level are shown in Figures 11-A and 11-B. The reduction in i_{corr} readings shown for all of the specimens except 1ML-

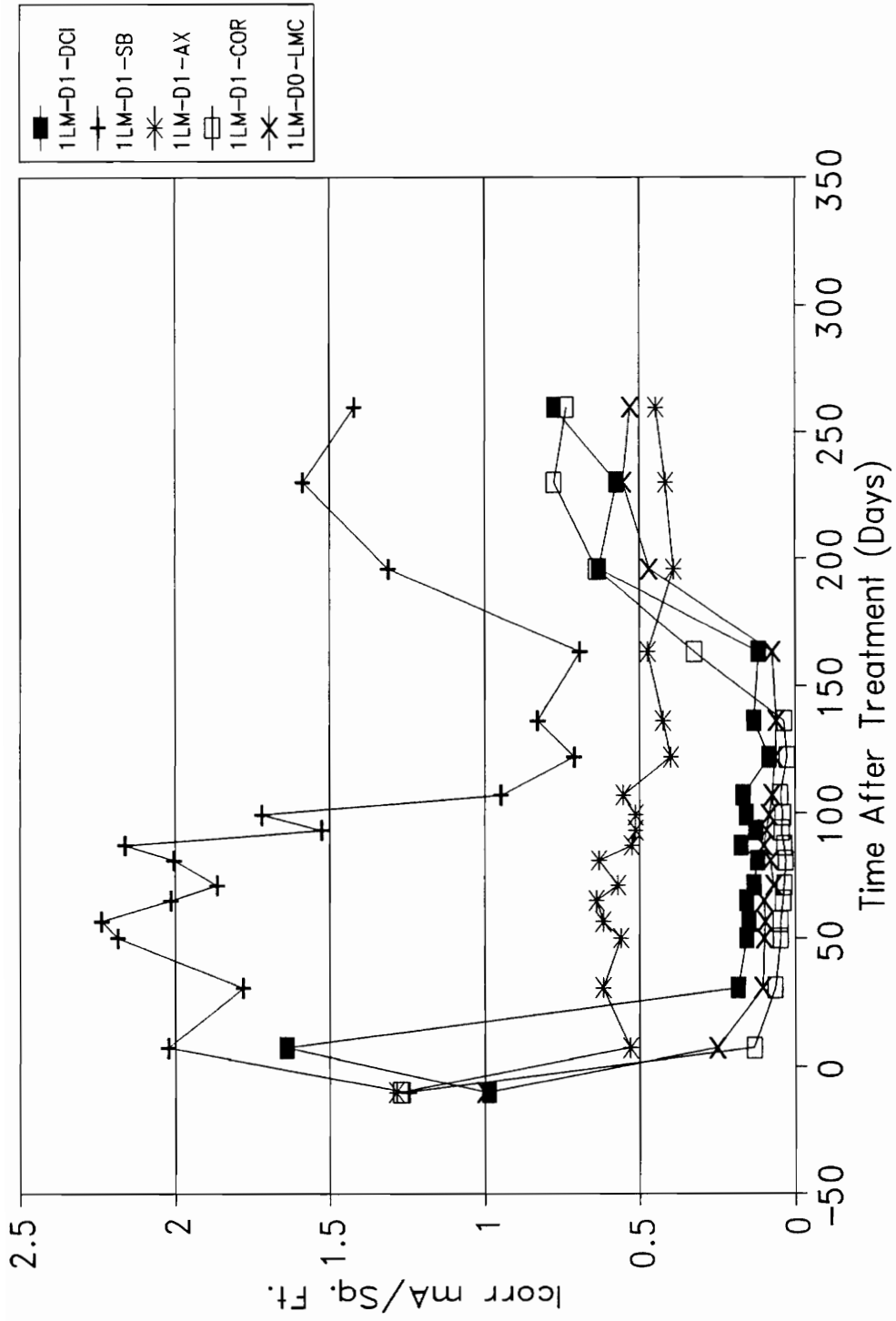


Figure 11 -A. Icorr Readings for Dried Specimens with Medium-Low Initial Corrosion Rates

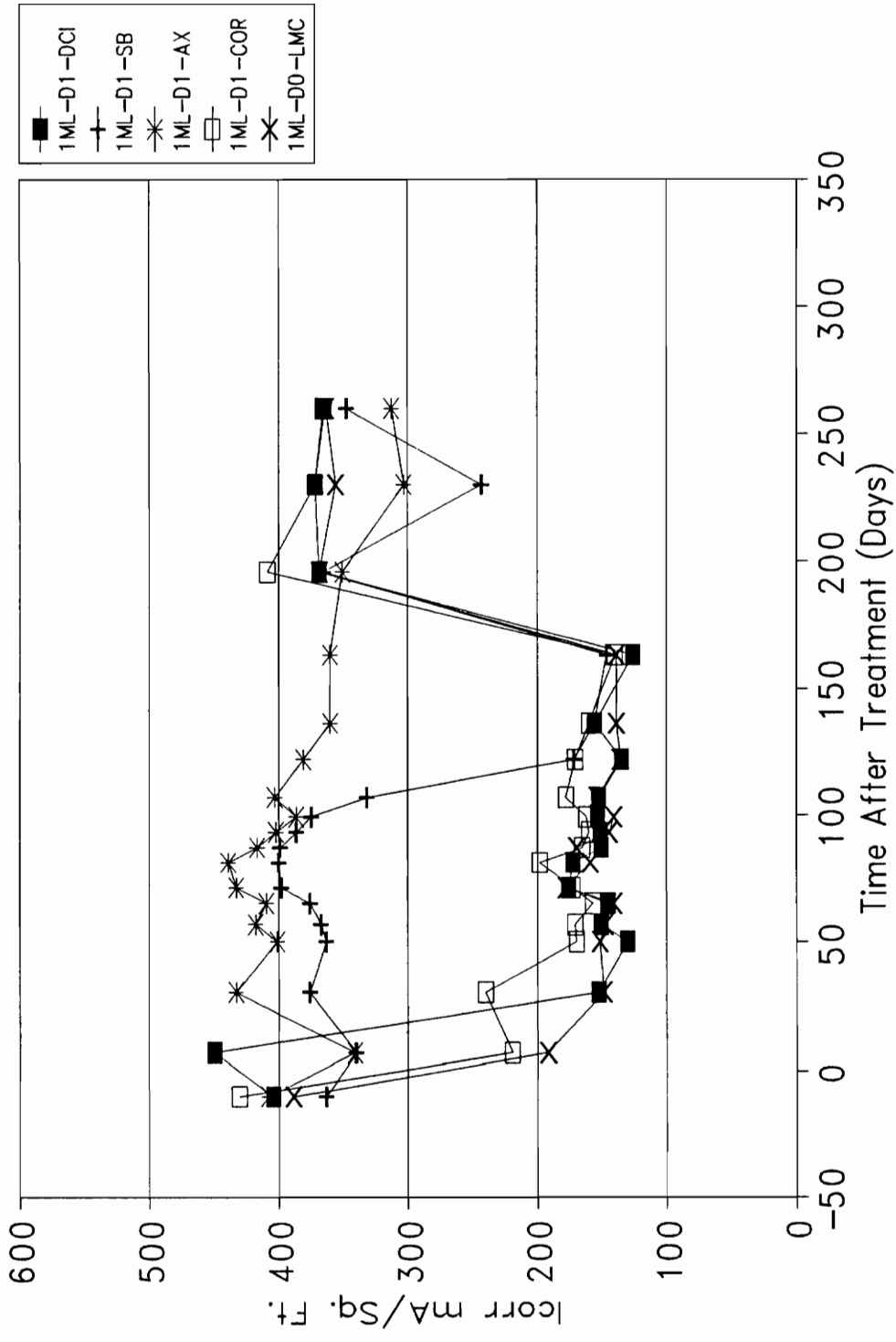


Figure 11-B. Ecorr Readings for Dried Specimens with Medium-Low Initial Corrosion Rates

D1-AX prior to 196 days after treatment are inaccurate. The resistors connecting the upper and lower mats of reinforcing steel on these specimens were discontinuous. The resistors were replaced between 163 and 196 days after treatment and all other specimens were checked for a similar problem. The rise in i_{corr} and E_{corr} seen in these specimens, 196 days after treatment, clearly demonstrates the effect of an increase in anode to cathode ratio. Overall, Alox was the best performing inhibitor in this group.

4.2.7 Low Initial i_{corr} , Dried Specimens

i_{corr} and E_{corr} measurements for the dried specimens with low initial corrosion rates are shown in Figures 12-A and 12-B. The highest pre-treatment i_{corr} reading for this group of specimens was 0.42 mA/ft^2 and the highest E_{corr} was 275 mV. Effectively, these specimens were barely corroding prior to treatment. Considering these observations, it is not surprising that the corrosion rate in the majority of the specimens increased after treatment. One exception to this trend was the specimen treated with DCI (1L-D1-DCI).

Previous studies have shown that calcium nitrite is effective as a corrosion inhibitor when included in the concrete during initial construction. Here the term inhibitor is being used according to its strict definition,

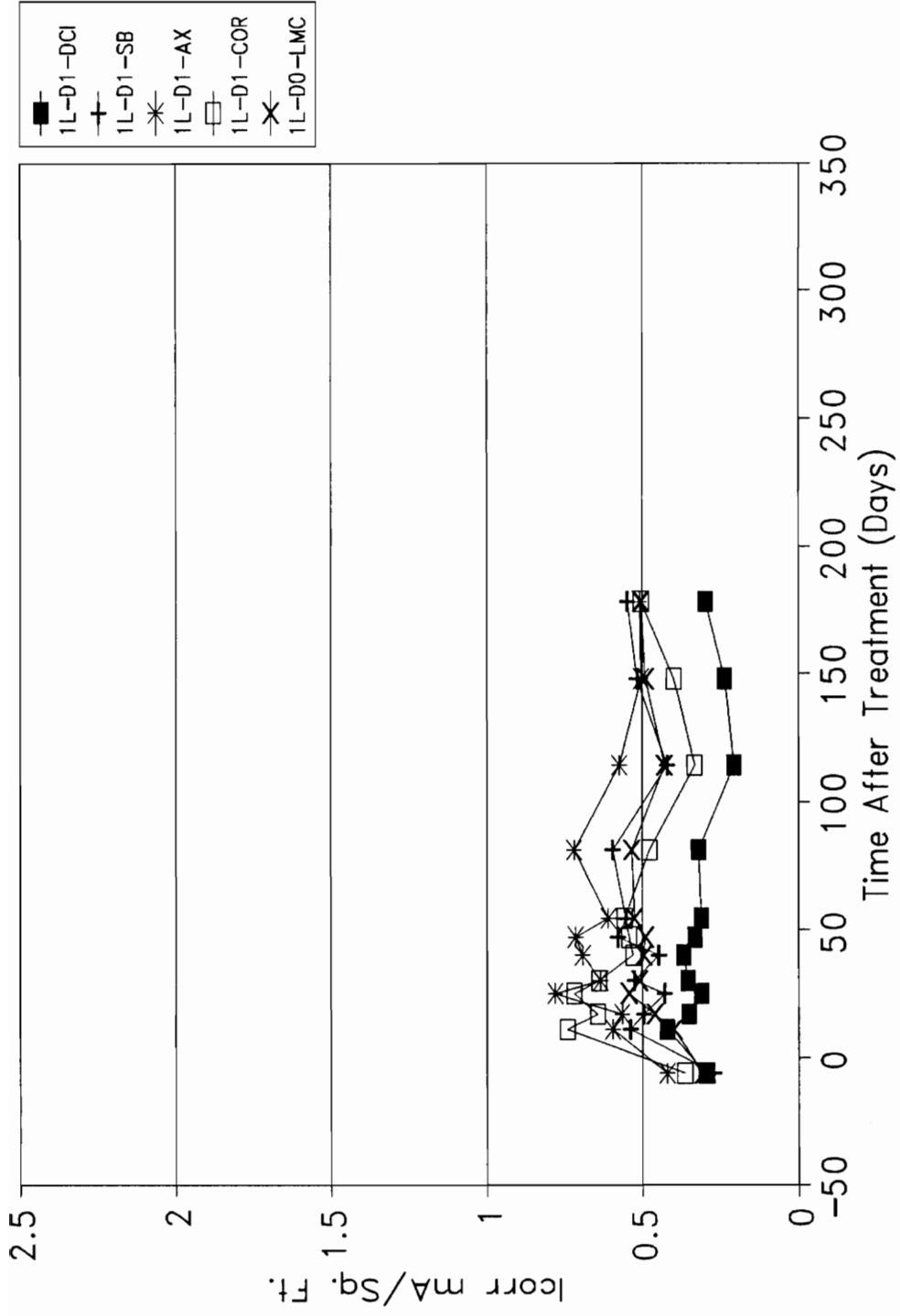


Figure 12-A. Icorr Readings for Dried Specimens with Low Initial Corrosion Rates

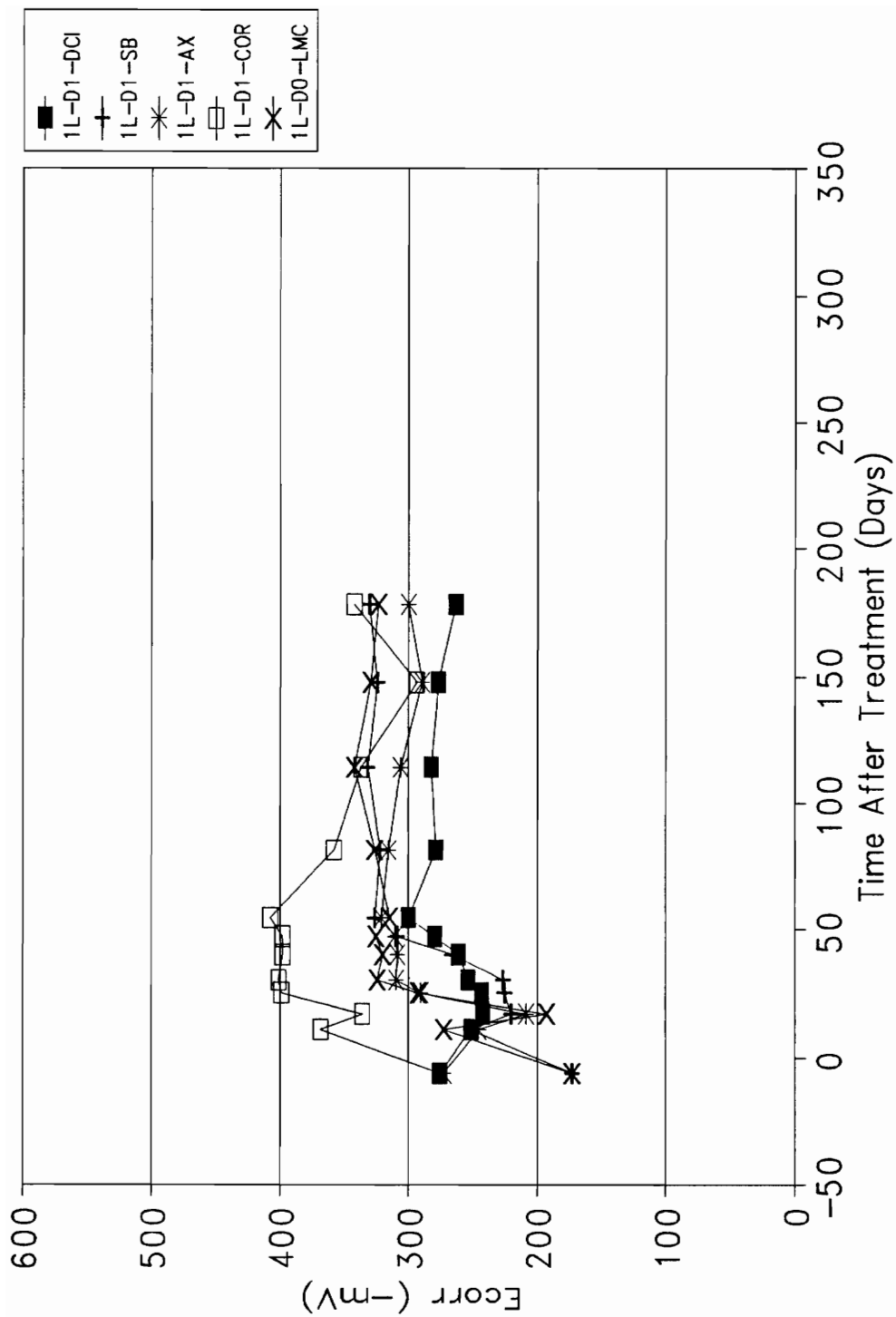


Figure 12-B. Ecorr Readings for Dried Specimens with Low Initial Corrosion Rates

which is "to check or repress" [54]. Calcium nitrite acts to repress the initiation of corrosion, where as this study is aimed at using inhibitors as chemical corrosion abatement treatments to arrest actively corroding reinforcement.

Treatments utilizing DCI seem to be effective on areas with low initial corrosion rates and may be effective at higher rates if a sufficient concentration of the inhibitor could be introduced to the corroding area. The concentration used for surface application on the small scale specimens was 0.1M as recommended in research performed by Dressman et al [55]. The concentration used in a similar study on U.S. 460 [56] was 15% solids by weight which is 11.4 times stronger than 0.1 M.

The chloride content prior to treatment, the estimated nitrite content at the bar level, the chloride:nitrite ratio, and the performance relative to the control are presented in Table 7 for each specimen treated with DCI. An examination of the specimens with chloride:nitrite ratios less than 2, reveals that all of these specimens performed somewhat better than the LMC control. This supports the theory that DCI would be effective if sufficient concentrations of nitrite could be introduced into treated area. The application of a 15% calcium nitrite solution to a non-dried treatment area should provide sufficient nitrite

to control corrosion up to a Cl^- concentration of 24.9 lbs/yd³ as calculated by Equation 15.

4.2.8 Alox Ponding and Modified Overlay Combinations

Since Alox is a hydrocarbon, it can not be included as

Table 7. Chloride:Nitrite Ratios for Specimens treated with DCI.

Specimen Code:	Cl^- lbs/yd ³	Estimated NO_2^- lbs/yd ³	$\text{Cl}^-:\text{NO}_2^-$ Ratio	Performed better than LMC
1H-D1-DCI	28.8	1.9	15.0	no
2ML-1-DCI	2.0	1.1	1.8	yes
2ML-2-DCI	1.8	1.1	1.6	yes
1M-1-DCI	12.8	1.1	11.6	no
1ML-D1-DCI	4.1	1.9	2.2	no
1L-D1-DCI	3.6	1.9	1.9	yes

an admixture in a concrete mix. Therefore, only the initial concentration of Alox absorbed by the specimen during ponding will be available to form a protective layer on the reinforcing steel. This raised concern over the long term effectiveness of the treatment. For this reason three additional specimens were treated, their post-treatment i_{corr} and E_{corr} measurements are shown in Figures 13-A and 13-B.

All three specimens were ponded with Alox, one was overlaid with LMC, one with a Cortec modified concrete, and one with DCI modified concrete. Sodium borate was excluded

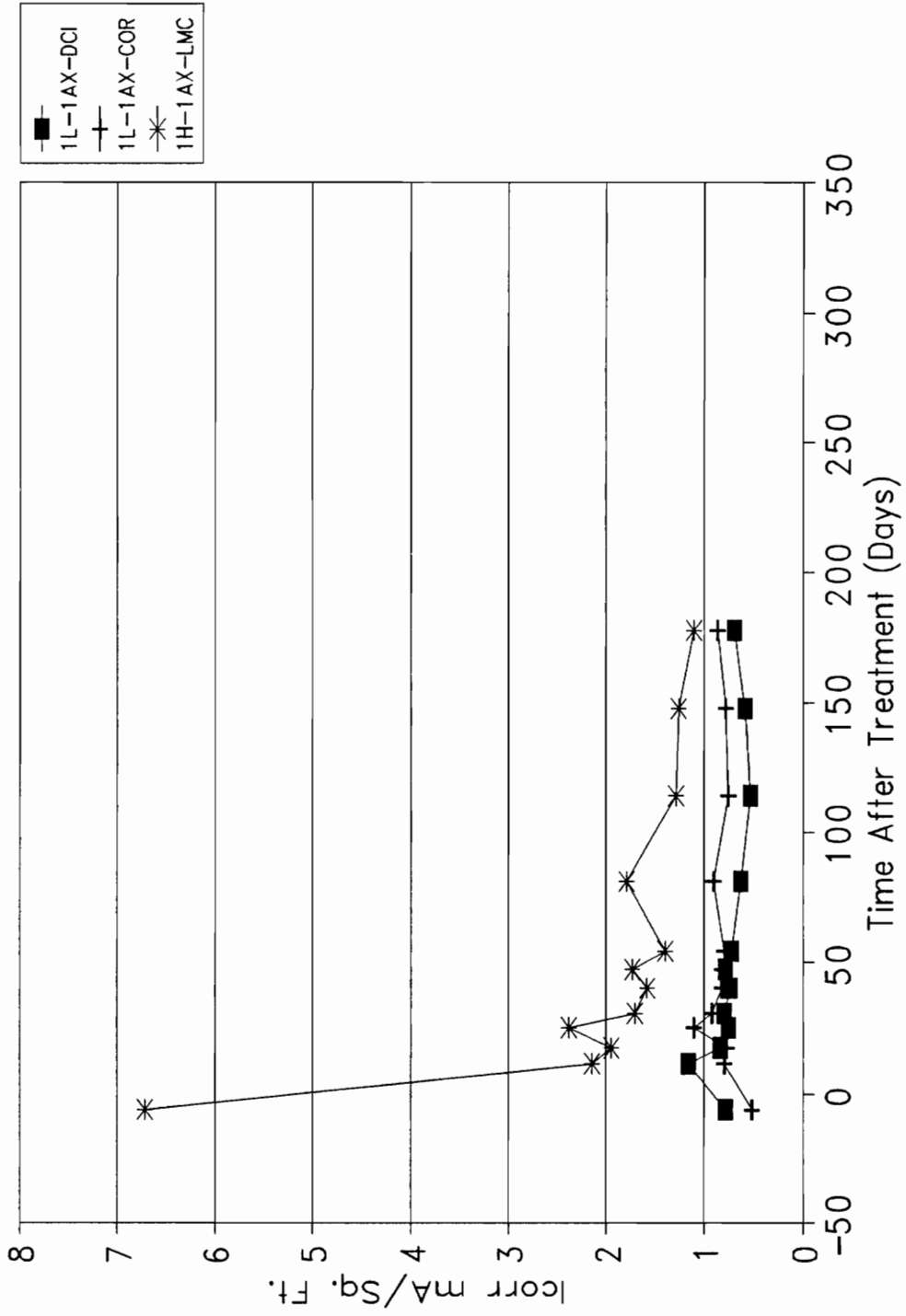


Figure 13-A. Icorr Readings for Alox Ponding and Modified Overlay Combinations

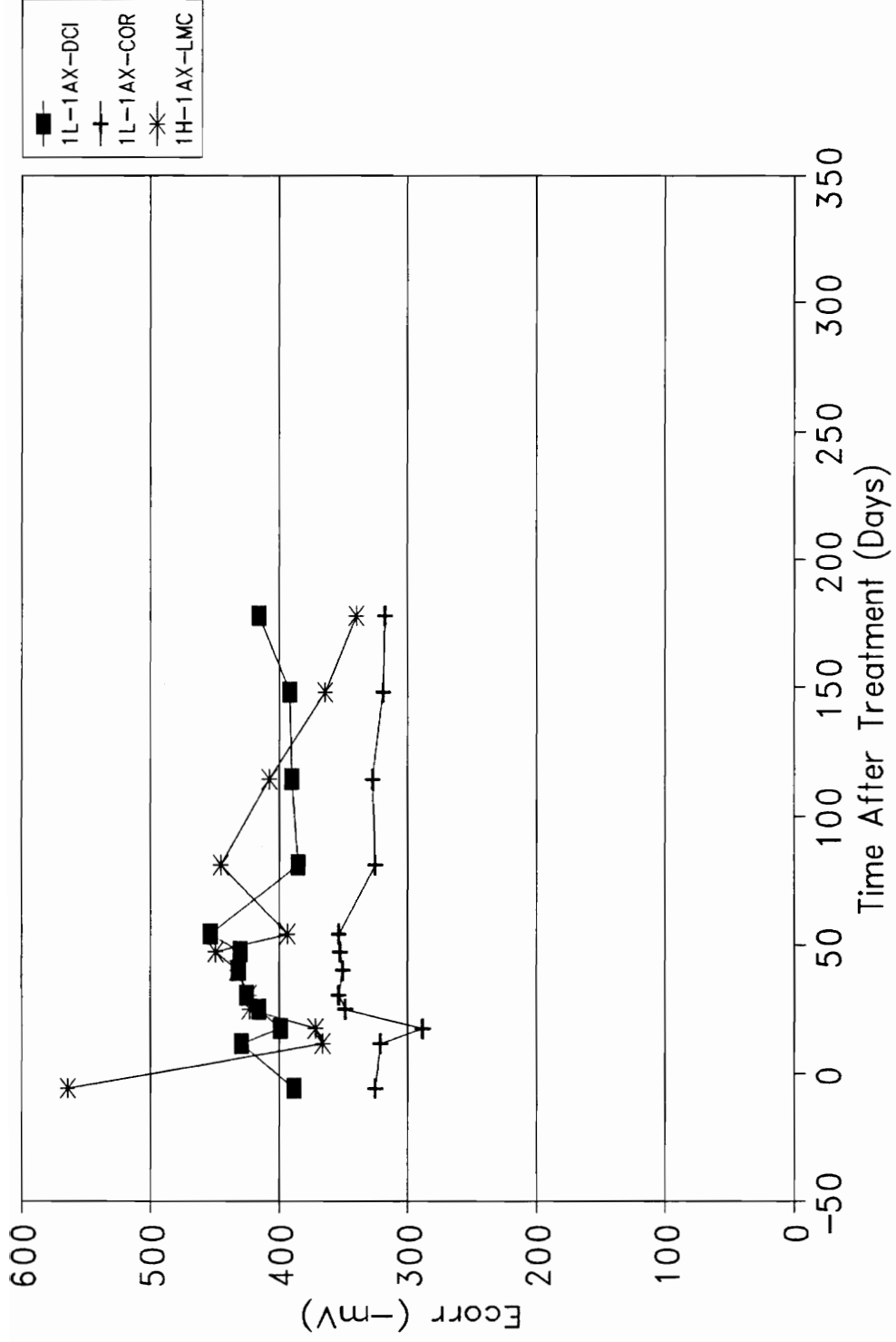


Figure 13-B. Ecorr Readings for Alox Ponding and Modified Overlay Combinations

since previous sets showed it to be ineffective corrosion inhibitor for the application investigated.

Specimen 1H-1AX-LMC displayed an 84% reduction in i_{corr} during the monitoring period. Unfortunately, the initial corrosion rates on the remaining 2 specimens were too low to show any meaningful change during the monitoring period.

4.2.8 Inhibitor Treatment Performance Summary

Two objectives were previously identified for the evaluation of the corrosion inhibitors, the first was to determine which, if any, of the inhibitors would be successful in the chemical abatement of corrosion. The second was to determine the most effective method of application.

Two inhibitors Alox and Cortec, demonstrated their ability to reduce corrosion, regardless of the pre-treatment i_{corr} . Alox seemed to perform better than Cortec if the specimens were not dried prior to ponding. This is probably due to the ethyl alcohol, used as a solvent, displacing some of the capillary water and allowing more of the inhibitor to be absorbed.

The LMC controls demonstrated the next best overall performance. Removing the chloride contaminated concrete above the rebar reduced the driving potential for the

corrosion reaction. In addition, the fresh concrete helped to reestablish the high pH normally found in uncontaminated concrete.

DCI proved to be an effective treatment when applied to specimens with low initial corrosion rates. Its lack of performance at higher i_{corr} rates may be concentration dependent as mentioned previously.

Though some specimens treated with sodium borate showed improvement, in no case did the inhibitor perform as well as the LMC controls.

No increased inhibitive effect could be discerned for non-dried specimens with similar i_{corr} values ponded for 2 days as compared to specimens ponded for only 1 day. The effectiveness of drying appears to be dependent on the type of inhibitor used and is discussed further in Section 4.6.

4.2.9 Normalized Inhibitor Performance

In order to better evaluate the performance of the inhibitors, an effort was made to separate the portion of reduction in i_{corr} due solely to the inhibitor from the improvement resulting from removing the chloride contaminated concrete.

Due to the variation in initial corrosion rates Equation 10, page 25, was used to calculate the percent

change in i_{corr} for the controls. Equation 16 was developed to determine the percent change of a treatment resulting from the application of the inhibitor.

$$\%Change_{inhb} = 100 \times \frac{(\%Change_{treatment} - \%Change_{control})}{\%Change_{control}} \quad (16)$$

Unfortunately, a plot of the percent change in the controls shown in Figures 14 and 15 shows that the reduction in i_{corr} is highly variable and dependent on the initial corrosion rate. Specimens with medium initial i_{corr} rates show the greatest initial reduction. Specimens with high initial corrosion rates display a time dependent reduction. Therefore, corrections based on the percent change of the controls could lead to large errors in the estimation of the inhibitors performance unless their initial i_{corr} rates were very close.

The relationship between Cl^- concentration and i_{corr} represents an alternative method to estimating the benefit of the inhibitors. Chloride samples were taken from 1H-D0-LMC and 1ML-0-LMC to determine the chloride content at the bar level. A comparison was made between the measured and predicted i_{corr} rates based on the Cl^- content using Equation 13, page 63. The comparison, and the prediction interval calculated for the relationship between Cl^- and i_{corr} are shown in Table 8.

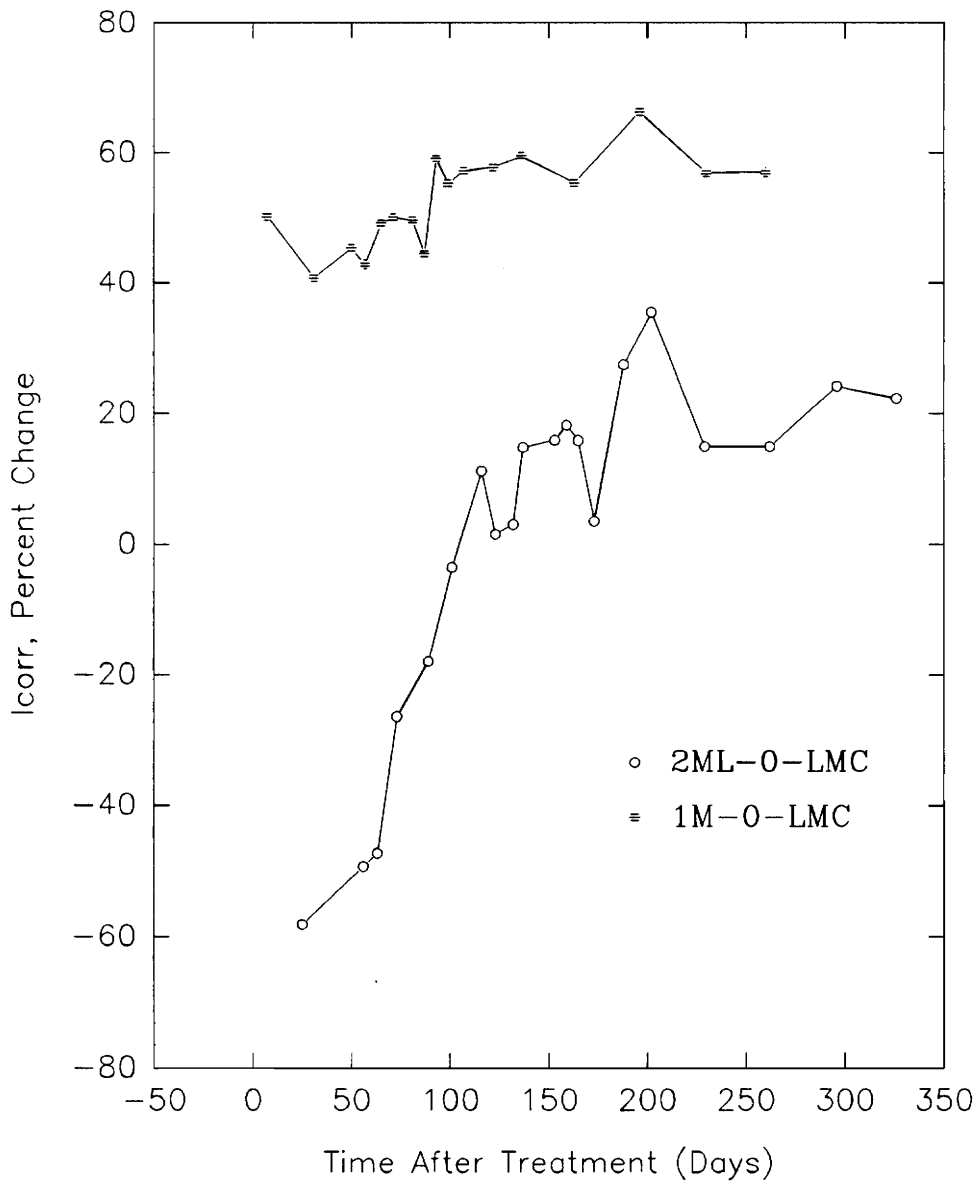


Figure 14. I_{corr}, Percent Change
For Non-Dried Specimens

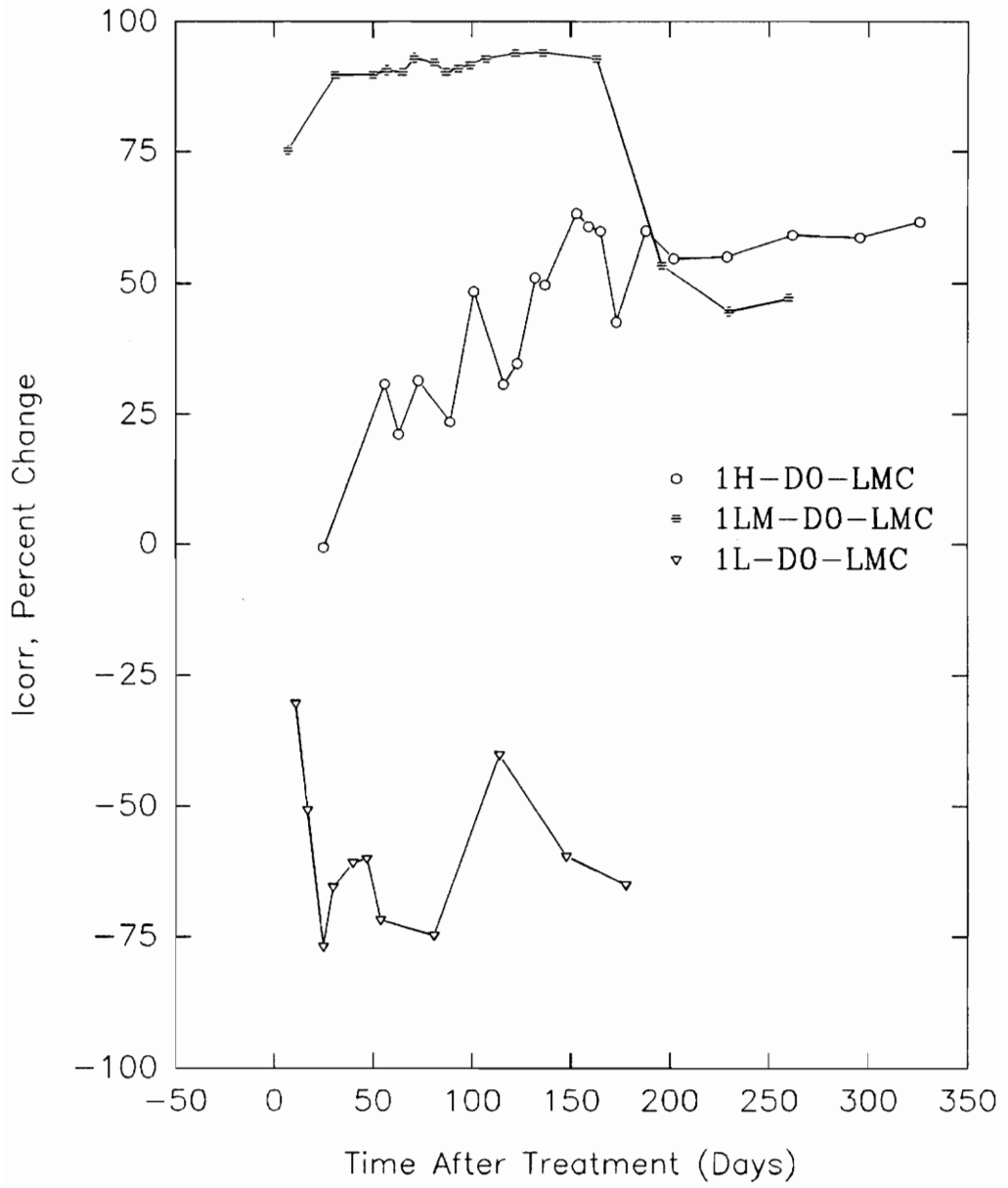


Figure 15. Icorr, Percent Change For Dried Controls

Table 8. Measured and predicted i_{corr} rates for the LMC Controls based on chloride contents taken 331 days after treatment.

Specimen	Measured i_{corr} (mA/ft ²)	Predicted i_{corr} (mA/ft ²)	95% Prediction Interval	95% Confidence Interval
2L-0-LMC	1.02	0.92	-1.36 - 3.21	0.46-1.39
1H-D0-LMC	3.73	5.58	3.30 - 7.87	5.12-6.05

The Cl⁻ contents for the specimens are shown in Appendix C, Table C-4. The prediction intervals were calculated using MINITAB Statistical Software. The prediction interval represents the range in which 95% of the i_{corr} measurements for a given chloride content would be found.

Since the measured corrosion rate for both control specimens are within the prediction interval, this relationship was used to calculate the expected reduction in i_{corr} resulting from the removal of the chloride contaminated concrete and the subsequent migration of Cl⁻ ions into the overlay, away from the reinforcing steel. The method accounts for the varied rates of Cl⁻ diffusion seen in the individual specimens. However, error is introduced from the regression equation. The results of these calculations are shown in Table 9.

Table 9. Estimation of the reduction in i_{corr} resulting from the application of the corrosion inhibitors.

Specimen	Measured i_{corr} (mA/ft ²)	Predicted i_{corr} (mA/ft ²)	Difference (mA/ft ²)	Percent Reduction ¹ (Inhibitor)
1H-D1-DCI	7.06	4.15	-2.91	-29.8%
1H-D1-SB	12.19	4.12	-8.07	-62.9%
1H-D1-AX	1.65	5.74	4.09	37.4% ²
1H-D1-COR	2.1	5.93	3.83	38.6%

¹ Percent Reduction was calculated by dividing the difference between the predicted and measured i_{corr} rates by the pre-treatment corrosion rate. A negative percent reduction indicates that the reduction of i_{corr} was less than what would be expected from the removal of the chloride contaminated concrete if no inhibitor had been applied.

² The predicted initial i_{corr} of 10.93 mA/ft² based on the Cl⁻ content was used to arrive at this percentage. If the measured i_{corr} of 37.48 mA/ft² is used, the reduction is 10.9%. The change was made based on earlier observations of the specimens measured initial i_{corr} .

As shown in Table 9, both Alox and Cortec have a sufficient effect on corrosion rate, beyond that obtained from removing the chloride contaminated concrete only, and thus should be included in the large scale laboratory evaluation, Phase III.

4.3 Evaluation of Bond Strength

The bond strength between the overlays and the substrate concrete was measured 160 days after the treatment of the first set of specimens. The cores were drilled at least 1½" away from the reinforcing steel in order to minimize any disturbance of the corrosion cell. The bond strength was measured at a minimum of 3 locations on each specimen. The results of these measurements are presented in Table 10.

A bond strength of 250 lbs was selected as the minimum bond strength needed to prevent the overlay from delaminating under freeze-thaw cycles and traffic loadings [57]. The average bond strength for 2 of the Alox and Cortec treated specimens was below this limit. All of the other treatments showed no reduction in bond strength.

The grout appeared to have cured on the specimens treated with Alox, but an oily residue was found between the cured grout and the base concrete. The grout on the specimens treated with Cortec was both porous and powdery. It generally disintegrated under the water pressure from the coring rig.

Table 10. ACI 503-R Overlay Bond Strength
Summary of Data for Inhibitor Modified
Concrete

Treatment	Specimen	Core #	Bond Strength (lbs)
Alox 901 Ponding LMC Overlay	1H-D1-AX	1	0
		2	0
		3	0
		AVG	0
		σ_{n-1}	0
	2ML-1-AX	1	0
		2	60
		3	80
		AVG	47
σ_{n-1}		42	
2ML-2-AX	1	250	
	2	220	
	3	300	
	AVG	257	
	σ_{n-1}	40	
Cortec 1337 Ponding Cortec 1609 Overlay	1H-D1-COR	1	0
		2	0
		3	0
		4	0
		AVG	0
	σ_{n-1}	0	
	2ML-1-COR	1	0
		2	80
		3	0
		AVG	27
		σ_{n-1}	46
	2ML-2-COR	1	460
2		370	
3		140	
AVG		323	
σ_{n-1}		165	

Table 10 Continued.

ACI 503-R Overlay Bond Strength
 Summary of Data for Inhibitor
 Modified Concrete

Treatment	Specimen	Core #	Bond Strength (lbs)	
DCI Ponding DCI Overlay	1H-D1-DCI	1	980	
		2	1000	
		3	710	
		AVG	897	
	σ_{n-1}			162
		2ML-1-DCI	1	920
			2	780
	3		550	
	AVG		750	
σ_{n-1}			187	
	2ML-2-DCI	1	1060	
2		970		
3		1080		
AVG		1037		
σ_{n-1}			59	
	Sodium Borate Pond & Overlay	1H-D1-SB	1	950
2			720	
3			720	
AVG			797	
σ_{n-1}				133
		2ML-1-SB	1	1200
			2	1000
3			620	
AVG			940	
σ_{n-1}			295	
	2ML-2-SB	1	900	
2		970		
3		940		
AVG		937		
σ_{n-1}			35	

Table 10 Continued.

ACI 503-R Overlay Bond Strength
 Summary of Data for Inhibitor
 Modified Concrete

Treatment	Specimen	Core #	Bond Strength (lbs)
LMC Overlay Cover Concrete Removed	1H-D0-LMC	1	1050
		2	1100
		3	890
		AVG	1013
		σ_{n-1}	110
	2ML-0-LMC	1	1250
		2	670
		3	630
		AVG	850
		σ_{n-1}	347
1" LMC Overlay	2M-LMC	1	960
		2	680
		3	650
		AVG	763
		σ_{n-1}	171
Thin Polymer Overlay	2L-TP	1	1380
		2	1100
		3	340 ¹
		AVG	NA
		σ_{n-1}	NA

¹ The third reading was taken over a Cl- hole filled with epoxy prior to overlay. The epoxy in the Cl- hole failed elastically during testing.

Three additional specimens were treated in an effort to improve the bond strength, 2 with Cortec and 1 with Alox. The Alox specimen and a Cortec specimen were first ponded with the inhibitor. After the excess inhibitor was removed, dry cement was dusted on the surface to absorb any residue. The powdered cement was removed by wire brushing and compressed air. The other Cortec specimen was dried under a heat lamp for 24 hours after the excess inhibitor was removed. The bond strength of these specimens was tested after 7 days curing. An LMC control was cast at the same time to determine the effect of the decreased curing time.

The bond strengths for these specimens are shown in Table 11-A. Though the specimen treated with Alox showed some improvement, it was not considered sufficient for field use. The decreased curing time had no significant effect on the LMC control.

A second attempt was made to improve the bond strength by sand-blasting the specimen prior to overlay. Both specimens ponded with Alox and Cortec were tested. In addition, a specimen was overlaid with concrete containing 2 lbs/yd³ of Cortec 1609. This specimen was not ponded. The bond strength for these specimens was measured after 7 days curing.

Table 11-A. ACI 503-R Overlay Bond Strength Summary of Data for Inhibitor Modified Concrete

Treatment	Core #	Bond Strength (lbs)
Alox 901 Surface Pond. Surface dusted with dry cement and wire brushed prior to overlay.	1	100
	2	40
	3	60
	AVG	67
	σ_{n-1}	31
Cortec 1337 Surface Pond. Surface dusted with dry cement and wire brushed prior to overlay.	1	0
	2	0
	3	0
	AVG	0
	σ_{n-1}	0
Cortec 1337 Surface Pond. Specimen dried under a heat lamp for 24 hours.	1	0
	2	0
	3	0
	AVG	0
	σ_{n-1}	0
LMC Control	1	740
	2	1020
	3	780
	AVG	847
	σ_{n-1}	151

The results of these tests are shown in Table 11-B. All of the specimens developed adequate bond strength. Therefore, light sand-blasting was used to improve bond strength for future treatment using Alox or Cortec.

Table 11-B. ACI 503-R Overlay Bond Strength
Summary of Data for Corrosion Inhibitor Modified Concrete

Treatment	Core #	Bond Strength (lbs)	Failure Plane
Alox 901 Surface Pond, Sandblasted prior to overlay	1	860	Base Concrete
	2	640	50/50 Base Concrete/Bond
	3	1240	50/50 Base Concrete/Bond
	AVG.	913	
	σ_{n-1}	304	
Cortec 1337 Surface Pond, Sandblasted prior to overlay	1	650	Grout Failure
	2	1040	50/50 Base Concrete/Bond
	3	860	50/50 Base Concrete/Bond
	AVG.	850	
	σ_{n-1}	195	
Cortec 1609 2 lbs/yd ³	1	940	Base Concrete Failure
	2	740	Base Concrete Failure
	3	830	Base Concrete Failure
	AVG.	837	
	σ_{n-1}	100	

4.4 Freeze Thaw Durability of Inhibitor Modified Concrete

Beams were cast for rapid freeze-thaw testing from the same mix designs used for the large scale specimens. In addition, beams were cast from a normal concrete mix without any inhibitors added as a comparison. The mixture

proportions, and properties of the fresh and hardened concrete are presented in Appendix A, Table A-14. The inhibitor modified beams were exposed to 315 cycles to date unless their deterioration warranted removal prior to that point. The normal concrete beams have been exposed to 265 cycles, and the latex beam to only 215 cycles to date. The air content of the plastic concrete, number of cycles of exposure, and durability factor are shown in Table 12. The mixture proportions are given in Appendix A, Tables A11-A13. The flexural and longitudinal frequencies are shown in Appendix C, Table C-5.

Table 12. Durability Factors for Inhibitor Modified Concrete

Mix Design	Initial Air Content	Number of Cycles of Exposure	Durability Factor ¹
DCI-M4	9.0 %	492	13.3
Cortec-M1	7.4%	315	100.0
Cortec-2-M1	6.4%	315	100.0
Cortec-M-4	6.5%	315	100.0
Normal-M1	6.8%	265	100.0
LMC-M2	10.5%	215	100.0

- 1 The calculated durability factor is the average of the 2 beams with the exception of the LMC beam.
- 2 Since the relative modulus dropped below 50% after 49 cycles the durability factor was calculated at 49 cycles. Further exposure led to the disintegration of the specimen.

From this data the only inhibitor which appears to have a detrimental effect on the freeze-thaw durability of the concrete is DCI. However, the author believes that this result is in error for the following reasons:

- 1) DCI has been used in the field for 26 years with no previous reports of significant freeze-thaw deterioration.
- 2) The mix had not reached its initial set 9 hours after the concrete was placed. This was originally believed to be the result of using very cold mix-water, but later evidence indicates a cement problem.
- 3) Similar problems were noticed with other mixes made with the same cement and high-range water reducers.
- 4) This mix exhibited a % decrease in 28 day strength compared to previous mixes.

Taramac cement was replaced with Riverton cement for the mixes in this study as noted in Appendix A, Tables A11-A13. New beams were cast from a DCI mixture prepared with Riverton cement. The beams had an initial air content of 5.3%. The mixture proportions and properties of the fresh and hardened concrete are presented in Appendix A, Table A-15. After 240 freeze-thaw cycles, the average durability factor for these beams was 91. The improved durability supports the previous contention.

4.5 Evaluation of Large Scale Specimens

The treatment of the large scale specimens provided an opportunity to test the field application methods prior to the field validation work to be conducted under the project sponsoring this work. Construction specifications were developed and are presented in Appendix D. In addition the large scale specimens should provided an indication of the likelihood of the treatments acting as dangerous inhibitors.

Since it would be difficult to pond the inhibitor on an entire deck, spray application techniques were developed. The specimens which were sprayed with Alox and Cortec were lightly sandblasted prior to overlay in order to improve bond strength. DCI was included in the large scale slab treatments at the manufacturers recommended concentration. This was done to test previous observations regarding the low calcium nitrite concentration.

4.5.1 Pre-Treatment Evaluation

A delamination survey indicated that the deck sections were sound. Two complete sets of potentials, icorr and chloride measurements were taken on the slabs prior to treatment. The survey results are shown in Appendix C, Tables C6-C7. Prior to treatment, damage to some of the slabs done at the time of removal from the PA I-80 deck prevented complete survey measurements. These areas are

shown as blanks in the previously mentioned tables. Potential measurements were taken on the transverse rebar between the longitudinal bars. i_{corr} measurements were performed with both the 3LP and the Geocisa device. The Geocisa device was included in hopes that its guard-ring electrode would confine the area of polarization and thus provide a more accurate assessment of treatment effectiveness. A simple linear regression based on 77 observations from the pre-treatment i_{corr} readings produced an r^2 of 0.6% indicating that no correlation could be made between the Geocisa and 3LP data.

All 3 slabs were in the medium-low initial i_{corr} category prior to treatment. The mean i_{corr} , as measured by the 3LP, was approximately 1 mA/ft² higher on the slab treated with DCI.

4.5.2 Inhibitor Performance

Due to the amount of time necessary to take i_{corr} readings on the slabs using both the 3LP and the Geocisa device, measurements were taken simultaneously on different slabs. Therefore, measurements were taken on the same date and not the same number of days before or after treatment. For this reason only trends can be compared. The complete data are shown in Appendix C, Tables C8-C11.

A comparison between the pre- and post-treatment potentials is shown in Table 13-A. All of the treatment

Table 13-A. Pre- and Post-Treatment Mean CSE Potential Readings for the Inhibitor Modified Slabs

Treatment	Pre-Treatment				Post-Treatment			
	Days Prior	-mV	Days Prior	-mV	Days After	-mV	Days After	-mV
Alox 901	77	318	50	300	34	273	52	233
Cortec	70	260	44	191	40	138	58	125
DCI	46	342	20	320	36	228	65	244

Table 13-B. Pre- and Post-Treatment Mean 3LP i_{corr} Readings (mA/ft²) for the Inhibitor Modified Slabs

Treatment	Pre-Treatment				Post-Treatment			
	Days Prior	i_{corr}	Days Prior	i_{corr}	Days After	i_{corr}	Days After	i_{corr}
Alox 901	77	1.28	50	1.16	34	2.94	52	2.29
Cortec	70	1.31	44	1.34	40	1.10	58	1.20
DCI	46	2.34	20	2.25	36	4.08	65	4.46

demonstrate a reduced potential after treatment. A comparison between pre- and post- 3LP i_{corr} readings is shown in Table 13-B.

The slabs treated with both Alox and DCI show an increase in i_{corr} as measured by the 3LP after treatment. This may be due in part to the overlay concrete increasing moisture content of the treated slab thereby allowing a greater area of polarization and/or decreasing the

concrete's resistance at the rebar level and thus increasing the corrosion rate. Another possible explanation is that the slabs dried out while being stored indoors, when the overlays were placed the added moisture reactivated the corrosion cell. However, the author finds this unlikely since the slabs were covered with saturated burlap and polyethylene sheeting for almost a month prior to the second set of pre-treatment readings. The second set of readings on the Alox slab demonstrate a decreasing trend in $3LP i_{corr}$. However, the mean value is still greater than the pre-treatment values.

The deck section treated with Cortec shows a 17% decrease in corrosion rate after treatment. All of the slabs will require additional monitoring to assess the effectiveness of the corrosion treatments. It must be noted that the objective of this phase of the study was to develop field application techniques.

Theoretically, the guard-ring electrode on the Geocisa device should confine the area of polarization and provide a better estimate of the corrosion activity after treatment. The mean pre- and post-treatment Geocisa i_{corr} measurements are shown in Table 13-C.

Table 13-C. Pre- and Post-Treatment Mean Geocisa i_{corr} Readings ($\mu\text{A}/\text{cm}^2$) for the Inhibitor Modified Slabs

Treatment	Pre-Treatment				Post-Treatment			
	Days Prior	i_{corr}	Days Prior	i_{corr}	Days After	i_{corr}	Days After	i_{corr}
Alox 901	77	.071	50	.073	34	.057	52	.074
Cortec	70	.132	44	.168	40	.035	58	.052
DCI	46	.107	20	.164	36	.315	65	.329

The slab treated with Alox demonstrated a 21% initial decrease in i_{corr} . The mean i_{corr} for the second set of readings was equal to pretreatment values. Cortec was shown to be very effective with a 77% decrease in i_{corr} from the mean pre-treatment readings. This reduction corresponds to the trend indicated by both the CSE potential and the 3LP i_{corr} measurements.

The deck section treated with DCI showed a 96% increase in corrosion rate between its highest pre-treatment average ($.164 \mu\text{A}/\text{cm}^2$) and the mean of its post-treatment average. This indicates an increase in corrosion activity after treatment even though the slab was sprayed with the manufacturers recommended concentration of DCI. Though this research indicates DCI may not be successful at corrosion abatement, long term data is needed to draw a firm conclusion.

4.5.3 Bond Strength Tests

Three cores were drilled into each of the treated slabs after 28 days curing. The average bond strengths measured for those cores is shown in Table 14.

The average bond strength for the slab treated with Alox 901 was below the acceptable limit of 250 lbs. Previous data had shown that a good bond could be obtained with sand blasting. The lower values shown here may indicate the need for more thorough sand blasting.

Table 14. Mean Bond Strengths for Inhibitor Modified Deck Slabs.

Treatment	Bond Strength, lbs
Alox 901	217
Cortec 1337/1609	410
DCI	680

The mean bond strengths for the other specimens were acceptable, though 1 measurement was below specifications on the Cortec slab. The complete data is presented in Appendix C, Table C11.

4.6 Prediction of Service Life

An estimation of the increase in treatment service life was calculated based on the reduction in corrosion rate of the small scale specimens. The estimate was made to assist

the engineer in assessing the treatments cost effectiveness. The estimation can not predict the actual time of inhibition provided by the inhibitors, nor does it include the possibility of premature failure due to debonding.

The prediction equation makes the following assumptions:

- 1) The service life of a typical LMC overlay is 20 years.
- 2) At the time of placement of a typical LMC deck overlay, 40% of the bridge deck is delaminated or spalled. The chloride contaminated concrete would be removed in these areas. Therefore, the average reduction of the non-dried LMC control specimens was used to represent the area of a bridge deck where the chloride contaminated concrete was removed. The average i_{corr} reduction for the controls is weighted by a factor of 0.4 since it represents only 40% of the components area in a typical rehabilitation.
- 3) The reduction in corrosion rate seen in specimen 2M-LMC was used to model the other 60% of a typical LMC deck overlay where the chloride contaminated cover concrete is left in place. The

reduction in i_{corr} was weighted by a factor of 0.6.

- 4) The corrosion rates on the deck at the time of rehabilitation are assumed to be equally represented by the specimens with low, medium-low, medium, and high initial corrosion rates, such that the average reduction seen in the small scale specimens could be used, with one exception. The results from the low initial i_{corr} dried specimens were not included.

The model is presented in Equation 17.

$$T_p = 20 \times \left[\frac{\%R_{\text{INHB}}}{(0.60(LMC_L) + 0.40(LMC_R))} \right] \quad (17)$$

where,

- T_p = Predicted service life (years)
- $\%R_{\text{INHB}}$ = Average percent reduction in corrosion rate of the inhibitor treated specimens.
- LMC_L = The percent reduction in corrosion rate of the LMC control specimen with the chloride contaminated concrete left in place.
- LMC_R = The average percent reduction in i_{corr} of the LMC control specimens with the cover concrete removed.

The percent reductions were calculated according to Equation 10 ,page 24, based on the last corrosion rate taken

in the monitoring period. The results of the calculation are shown in Table 15.

Table 15. Service Life Predictions

Treatment	Predicted Service Life
Alox 901, 1 Day Ponding ¹	46 years
Cortec 1337/1609, 1 Day Ponding	26 years
Alox 901, Dried and 1 Day Ponding	42 years
Cortec 1337/1609, Dried and 1 Day Ponding	34 years

¹ The predicted initial i_{corr} of 10.93 was used to calculate the percent reduction, not the measured value of 37.48.

From this estimation, Alox provides a 100% increase in service life. It should also be noted that drying provides no increase in estimated service life for the Alox treatments. It would also appear that the concrete would need to be dried prior to the application of Cortec in order to gain a significant benefit.

DCI treatment service life estimates could not be calculated using Equation 17, since only 1 of the small scale specimens in the non-dried 1 day pond group and 1 specimen in the dried group had chloride nitrite:ratios less than 2, resulting from the recommended low calcium nitrite treatment concentration discussed previously.

Recent research indicates most bridge decks will be

rehabilitated when 6% of the deck area is unsound (spalls, delaminations and asphalt patches) [58]. The results of a sensitivity analysis on Equation 17 are shown in Figure 16. A simple linear relationship was used to estimate the effect of the area of unsound concrete at the time of rehabilitation of a typical LMC deck on the predicted service life of the inhibitor treatments. Figure 16 indicates that the area of unsound concrete when a typical LMC overlay is placed has little effect on the predicted service life of the inhibitor treatments based on this model. Further research is needed to obtain a better estimate of the relationship.

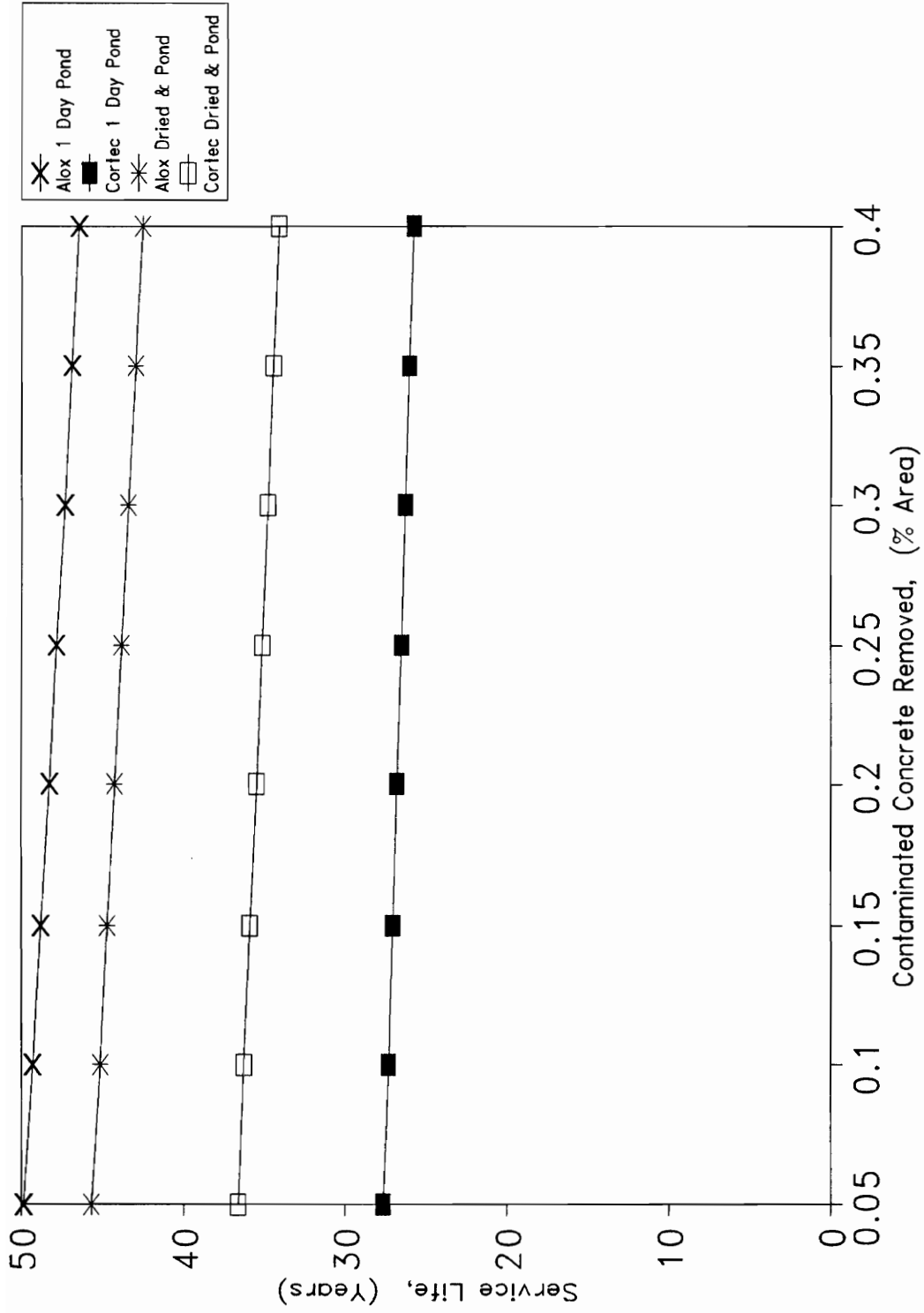


Figure 16. Sensitivity Analysis of Service Life Predictions Based on % Area

5.0 Conclusions

The following conclusions can be made from the preceding research:

1. The removal of the chloride contaminated concrete above the reinforcing steel and its subsequent replacement with fresh concrete is an effective means of reducing corrosion.
2. The removal of the cover concrete facilitates the direct application of corrosion inhibitors.
3. Alox 901 is a very effective surface applied corrosion inhibitor potentially capable of doubling an overlays service life.
4. Cortec 1307 and Cortec 1609 are effective inhibitors when applied as ponding agents and concrete admixtures respectively.
5. Alox 901 and Cortec 1337 have a detrimental effect on bond strength. This problem can be mitigated with sand-blasting.
6. DCI (calcium nitrite) is somewhat effective at reducing low corrosion rates when applied at the .1M concentration.
7. Cortec 1609 has no adverse effects on the freeze-thaw durability of concrete.

8. A correlation can be derived between the chloride content at the bar level and the corrosion rate of the reinforcing steel for laboratory conditions where moisture content and temperature are relatively constant.
9. No advantage is gained by ponding corrosion inhibitors for 2 days as opposed to 1 day.
10. No comparison can be made between the i_{corr} measured with the 3LP and the i_{corr} measured by the Geocisa device.

6.0 Recommendations for Further Research

Based on the limited time and scope of this study, the following recommendations can be made for further research:

1. In order to more accurately predict the service life of inhibitor treatments, long term monitoring to determine the period of inhibition needs to be conducted.
2. The chloride threshold for the initiation of corrosion after treatment should be determined in order to gain a better idea of the effectiveness of inhibitors.
3. Further research should be conducted towards the improvement of overlay bond strength.
4. Freeze-thaw testing should be repeated using DCI as an admixture to determine whether or not the inhibitor caused the deterioration observed in this study.
5. A better corrosion rate measurement device which utilizes a guard-ring electrode should be developed. Notebook personal computers currently on the market should be considered for controlling the device.
6. Additional large scale testing should be conducted to ensure that the inhibitors do not react as dangerous inhibitors when applied in the field.

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Appendix A

Materials

Table A-1. Virginia A4AE Bridge Deck Air Entrained Concrete, Batch Quantities, Pounds per Cubic Yard.

<u>Item</u>	<u>SSD Basis</u>
Cement	635
Water	212
Fine Aggregate	1200
Coarse Aggregate	1878
Air Entrainment Agent (AEA)	8.0 oz
Super Plasticizer	19.2 oz
Air Content	5.5 %
Slump	2 ½ "

Table A-2. Concrete Batch Quantities and Mix Characteristics for 1" Cover Depth Specimens.

<u>Item</u>	<u>SSD Basis</u>
Cement	635
Water	204
Coarse Aggregate	1882
Fine Aggregate	1208
AEA	8.0 oz
Superplasticizer	19.2 oz

Table A-3. Gradation of Coarse and Fine Aggregates, Percent Passing.

Sieve No.	Fine Agg.	Coarse Agg.
1/2"	100	100
3/8"	99.1	97.5
# 4	96.1	14.0
# 8	83.2	0.8
# 16	68.6	0.7
# 30	47.6	0.6
# 50	11.8	0.5
# 100	1.7	0.4
# 200	0.2	0.2
Pan	0.0	0.0

Table A-4. Properties of Coarse and Fine Aggregate.

Property	Fine Agg.	Coarse Agg.
Bulk Specific Gravity, Dry Basis	2.58	2.58
Bulk Specific Gravity, SSD Basis	2.58	2.60
Absorption, (%)	0.16	0.69
Fineness Modulus	2.92	—
Dry Rodded Unit Weight (lbs)	—	91.3

Table A-5. Cortec 1609 Modified Mix Designs, SSD Basis Batch Quantities (lbs) and Properties of Fresh and Hardened Concrete for Small Scale Specimen Overlays.

Batch Number	1	2	3
Type I Cement	637	631	632
Water	292	305	304
Fine Aggregate	1118	1107	1108
Coarse Aggregate	1929	1912	1913
Cortec 1609	1	1	1
AEA (ml)	188	224	184
W/C Ratio	0.46	0.48	0.48
Slump (inches)	2.50	0.75	1.25
Entrained Air (%)	5.7	3.8	6.6
Unit Weight (lbs/ft ³)	137	146	142
1 Day Strength (psi)	1990	2350	2110
7 Day Strength (psi)	3960	4580	4120
28 Day Strength (psi)	4740	5450	4640

Table A-6. DCI Modified Mix Designs, SSD Basis Batch Quantities (lbs) and Properties of Fresh and Hardened Concrete for Small Scale Specimen Overlays.

Batch Number	1	2	3
Type I Cement	653	647	647
Water	251	264	264
Fine Aggregate	1146	1135	1135
Coarse Aggregate	1978	1960	1960
DCI (gallons)	6	6	6
Daratard 17 (oz)	39.2	33.6	25.9
Daracen 100 (oz)	78.3	96.1	77.6
AEA (ml)	194	229	229
W/C Ratio	0.46	0.49	0.49
Slump (inches)	1.50	0.50	1.50
Entrained Air (%)	5.5	4.2	6.1
Unit Weight (lbs/ft ³)	138	144	143
1 Day Strength (psi)	3380	2090	2980
7 Day Strength (psi)	6070	6170	5200
28 Day Strength (psi)	6650	7560	6470

Table A-7. Latex Modified Mix Designs, SSD Basis Batch Quantities (lbs) and Properties of Fresh and Hardened Concrete for Small Scale Specimen Overlays.

Batch Number	1	2	3
Type I Cement	691	687	696
Water	110	130	108
Fine Aggregate	1578	1567	1589
Coarse Aggregate	1361	1344	1364
Latex	206	205	208
W/C Ratio	0.33	0.35	0.31
Slump (inches)	6.0	8.5	5.0
Entrained Air (%)	7.9	11.0	11.0
Unit Weight (lbs/ft ³)	133	131	130
1 Day Strength (psi)	2670	2610	2880
7 Day Strength (psi)	4080	3800	4300
28 Day Strength (psi)	4700	4750	4970

Table A-8. Sodium Borate Modified Mix Designs, SSD Basis
Batch Quantities (lbs) and Properties of
Fresh and Hardened Concrete for Small Scale
Specimen Overlays.

Batch Number	1	2	3
Type I Cement	622	637	637
Water	325	292	292
Fine Aggregate	1094	1118	1118
Coarse Aggregate	1897	1929	1929
Sodium Borate (in Mix Water)	11.6	11.6	11.8
AEA (ml)	160	164	223
W/C Ratio	0.52	0.46	0.46
Slump (inches)	1.50	4.25	2.00
Entrained Air (%)	3.0	4.9	6.8
Unit Weight (lbs/ft ³)	140	145	140
1 Day Strength (psi)	1340	1340	0
7 Day Strength (psi)	3540	3280	3900
28 Day Strength (psi)	4460	4280	NA

Table A-9A. Application Procedure for Thin Polymer Overlay.

1. Sandblast area to be overlaid.
2. Immediately apply epoxy-urethane co-polymer (Poly-Carb Mark-163 FLEXOGRID) at the rate of 2 pounds per square yard.
3. Broadcast fine aggregate (see Table A-9B for gradation) until there is an excess.
4. Wait 1-2 hours, then air blast surface to remove excess aggregate.
5. Apply a second coat of the epoxy-urethane co-polymer at the rate of 4 pounds per square yard.
6. Repeat steps 3 and 4.

Table A-9B. Gradation of Fine Aggregate, Morie #3 Basalt.

U.S. Standard Sieve	% Retained	% Passing
# 6	0.1	99.9
# 12	94.3	5.6
# 20	5.6	0.0
# 30	0.0	0.0

Table A-10. Hot-Mix Asphalt Mix Design.
Virginia SM-5

Gradation

Sieve Size	Percent Passing
1/2 in.	100.0
3/8 in.	97.4
No. 4	71.8
No. 8	45.5
No. 16	31.2
No. 30	23.0
No. 50	15.9
No. 100	10.7
No. 200	8.2

Marshall Results Using 50 Blows Compaction

VTM = 5.4 percent

VMA = 17.9 percent

VFA = 69.5 percent

Stability = 1950 lb

Flow = 1950 lb

Flow = 14.7

Density = 147.1 pcf

Asphalt content = 5.4 percent

Table A-11. Cortec 1609 Modified Mix Designs, SSD Basis Batch Quantities (lbs) and Properties of Fresh and Hardened Concrete for Large Scale Specimen Overlays.

Batch Number	1	2	3	4 ¹
Type I Cement	714	714	714	713
Water	308	307	320	309
Fine Aggregate	1588	1589	1586	1587
Coarse Aggregate	1361	1361	1352	1360
Cortec 1609	1	1	1	1
AEA (ml)	217	217	217	217
W/C Ratio	0.43	0.43	0.43	0.43
Slump (inches)	2.50	2.25	2.25	5.50
Entrained Air (%)	6.9	6.5	5.5	6.5
Unit Weight (lbs/ft ³)	141	143	144	138
7 Day Strength (psi)	4260	4580	4620	3660
28 Day Strength (psi)	5750	5630	5930	4730

¹ Freeze-Thaw Specimen Cortec-M-4 cast from this mix.

Table A-12. DCI Modified Mix Designs, SSD Basis Batch Quantities (lbs) and Properties of Fresh and Hardened Concrete for Large Scale Specimen Overlays.

Batch Number	1	2	3	4 ¹
Type I Cement	678	673	678	681
Water	265	276	265	259
Fine Aggregate	1138	1128	1138	1142
Coarse Aggregate	1955	1939	1955	1963
DCI (gallons)	6	6	6	6
Daratard 17 (oz)	27.1	26.9	27.1	27.2
Daracen 100 (oz)	54.3	53.8	54.3	54.4
AEA (ml)	231	229	231	210
W/C Ratio	0.47	0.49	0.47	0.46
Slump (inches)	1.5	6.0	8.0	3.25
Entrained Air (%)	6.4	13.5	16.0	9.0
Unit Weight (lbs/ft ³)	NA	NA	NA	135.0
7 Day Strength (psi)	4970	NA	1950	3980
28 Day Strength (psi)	6130	3410	2470	4700

¹ Freeze-Thaw Specimen DCI M-4 cast from this mix.

Table A-13. Latex Modified Mix Designs, SSD Basis Batch Quantities (lbs) and Properties of Fresh and Hardened Concrete for Large Scale Specimen Overlays.

Batch Number	1	2 ¹
Type I Cement	690	693
Water	124	117
Fine Aggregate	1573	1580
Coarse Aggregate	1350	1356
Latex	205	206
W/C Ratio	0.34	0.33
Slump (inches)	9.5	9.0
Entrained Air (%)	10.0	10.5
Unit Weight (lbs/ft ³)	134	134
7 Day Strength (psi)	3700	3820
28 Day Strength (psi)	4020	4000

¹ Freeze-Thaw Specimen LMC M-2 cast from this mix.

Table A-14. Normal Concrete Mix Designs, SSD Basis Batch Quantities (lbs) and Properties of Fresh and Hardened Concrete for Freeze-Thaw Testing.

Batch Number	1 ¹
Type I Cement	729
Water	315
Fine Aggregate	1625
Coarse Aggregate	1399
AEA (ml)	233
Daracem 100 (oz)	29.0
W/C Ratio	0.43
Slump (inches)	3.50
Entrained Air (%)	6.8
Unit Weight (lbs/ft ³)	142
7 Day Strength (psi)	4500
28 Day Strength (psi)	5490

¹ Freeze-Thaw Specimen Normal M-1 cast from this mix.

Table A-15. DCI Modified Mix Designs, SSD Basis Batch Quantities (lbs) and Properties of Fresh and Hardened Concrete for Freeze-Thaw Testing.

Batch Number	1 ¹
Type I Cement	658
Water	214
Fine Aggregate	1103
Coarse Aggregate	1896
AEA (oz)	4.9
Daracem 100 (oz)	79.0
Daratard 17	13.2
DCI (gallons)	6
W/C Ratio	0.40
Slump (inches)	1.0
Entrained Air (%)	5.3
Unit Weight (lbs/ft ³)	144.5
1 Day Strength	3180
7 Day Strength (psi)	6740
28 Day Strength (psi)	7660

¹ Freeze-Thaw Specimen DCI Remix cast from this mix.

Appendix B

Procedures

ACI 503R-30, Field Test for Surface Soundness and Adhesion

1. Core through the overlay concrete and down $\frac{1}{4}$ " into the substrate with a water cooled diamond core bit. The core bit should be of such size to produce a cored disc 2" in diameter.
2. Bond a standard $1\frac{1}{2}$ " diameter pipe cap with the bottom surface machined smooth and shoulder cut to produce a 2" diameter surface to the cored disk. A rapid curing epoxy compound adhesive such as PolyCarb MARK 198.3 should be used to produce the bond. The set time of the epoxy may be reduced by heating the pipe cap with a propane torch. The cored disc should not be heated.
3. Once the epoxy has cured, A $1\frac{1}{2}$ " pipe plug with an eye hook threaded through its center is screwed into the pipe cap. The eye hook is connected to the lower shackle of a Dillon 0-2000 lb 5" dial Dynamometer. The upper shackle of the dynamometer is connected by an eye hook to a threaded shaft. Grade 40, 4" diameter structural steel pipe with a $1\frac{1}{4}$ " flange at the base and machined plug at the top supports the load arm. The load arm consists of

a threaded nut with arms added to provide leverage. The nut rests on bearings set into the cap of the structural steel pipe. A keyway in the threaded shaft prevents it from rotating when the load handle is turned.

4. Tension is applied to the pipe cap by rotating the load handle counter-clockwise at a rate of approximately 100 lb per second.
5. The tensile load is indicated on the dynamometer. The tensile load required to separate the cored overlay disk from the substrate, and the failure plane are recorded.

Appendix C

Data

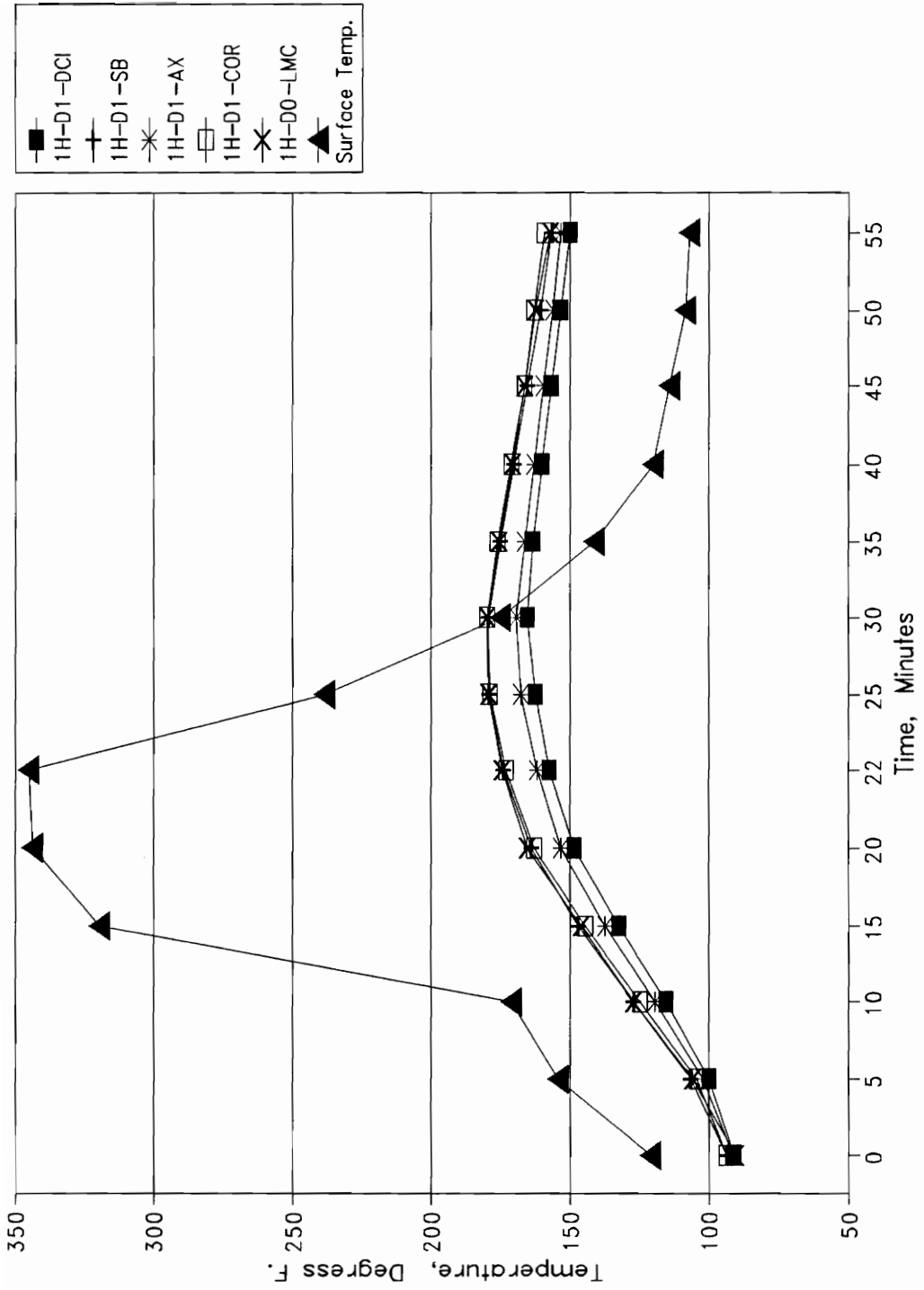


Figure C-1, Drying Temperatures Dea. F. for High Initial Corrosion Rate Specimens

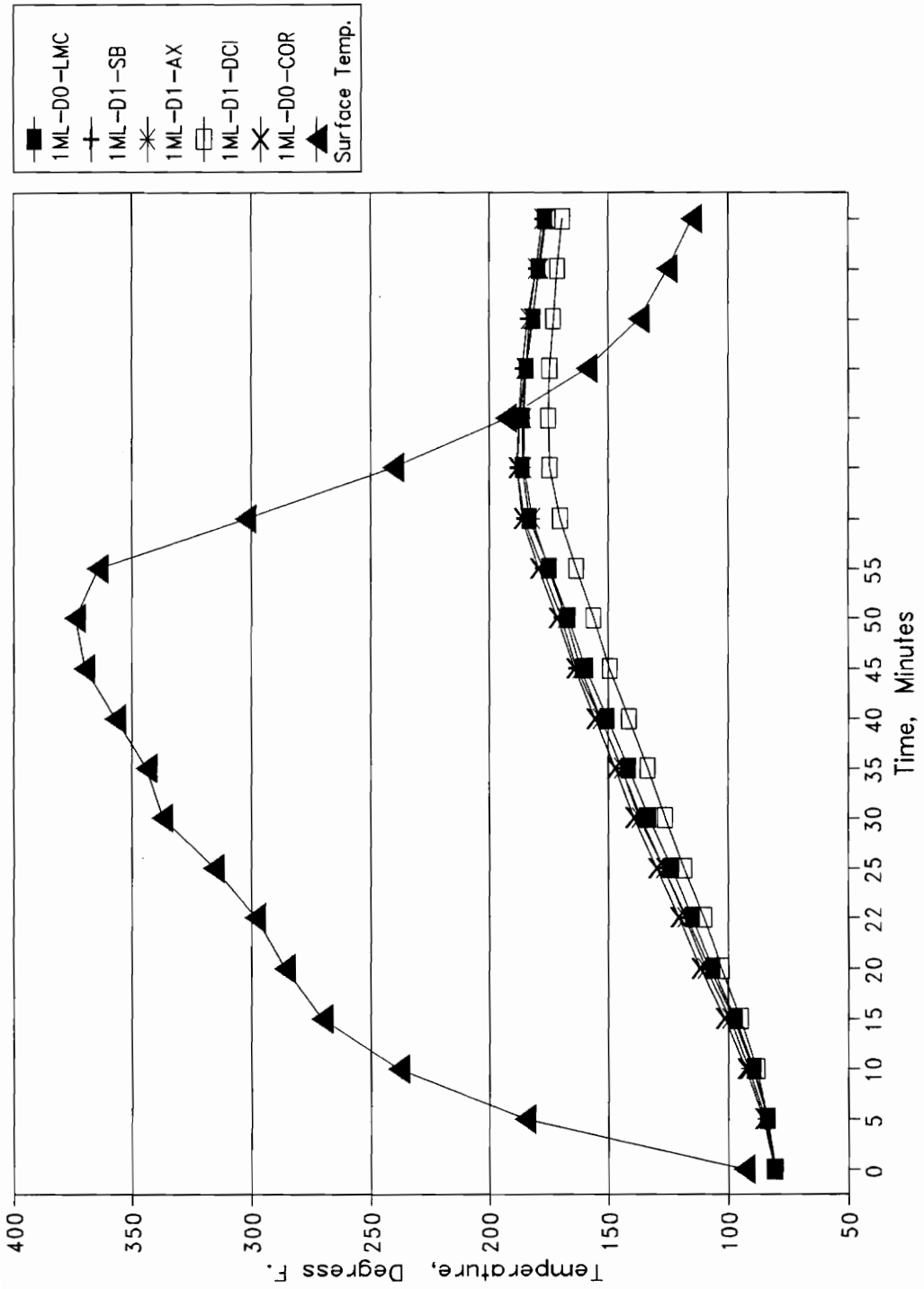


Figure C-2, Drying Temperatures Deg. F., ML Initial Corrosion Rate Specimens

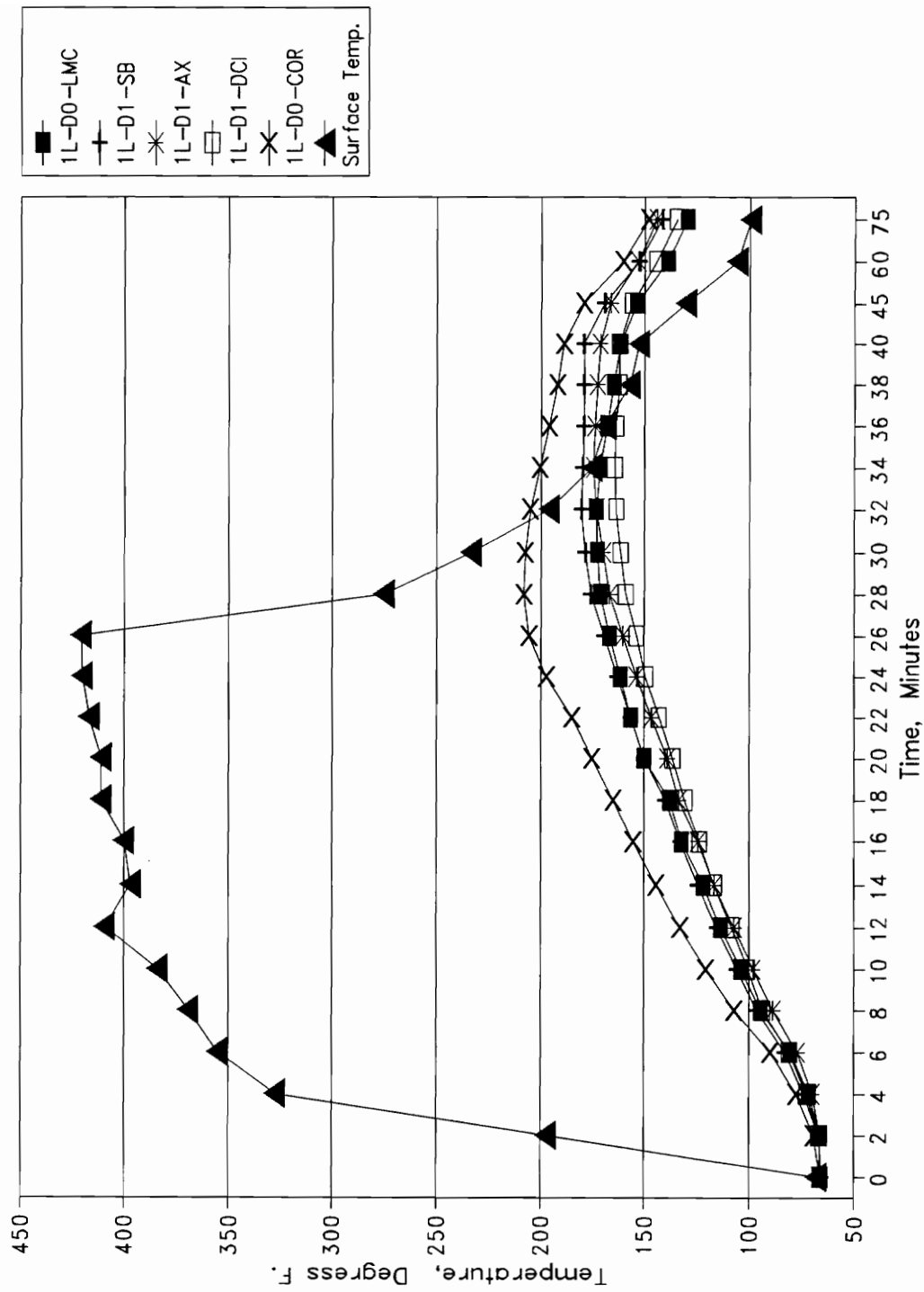


Figure C-3, Drying Temperatures Deg. F., Low Initial Corrosion Rate Specimens

Note: For following Chloride Content Tables, the following sample depth designations apply:

A = 1/4 to 3/4 "

B = 3/4 to 1 1/4 "

C = 1 1/4 to 1 3/4 "

D = 1 3/4 to 2 1/4 "

E = 2 1/4 to 2 3/4 "

These codes trail the specimen identification code.

Table C-4 Pretreatment Chloride Contents

Corrosion Inhibitor Evaluation		SHRP C-103 CHLORIDE CONTENTS		PROBE: A	DATE: 6/23/91
Specimen	Measured mV	Measured % Cl	Predicted % Cl	Predicted lbs/cy	Standard % Cl
1H-D1-DCI-A	NA				
1H-D1-DCI-B	21.2	0.0807	0.7192	28.8	
1H-D1-SB-A	19.9	0.0857	0.7689	30.8	
1H-D1-SB-B	23.1	0.0739	0.6517	26.1	
1H-D1-AX-A	20.8	0.0822	0.7342	29.4	
1H-D1-AX-B	22.2	0.0770	0.6830	27.3	
1H-D1-COR-	20.5	0.0833	0.7456	29.8	
1H-D1-COR-B	24.8	0.0683	0.5961	23.8	
1H-D1-LMC-	20.3	0.0841	0.7533	30.1	
1H-D1-LMC-B	24.1	0.0706	0.6185	24.7	
2L-1-DCI-A	NA				
2L-1-DCI-B	33.5	0.0457	0.3704	14.8	
2L-1-DCI-C	41.8	0.0311	0.2245	9.0	
2L-1-DCI-D	59.4	0.0138	0.0493	2.0	0.0329
2L-1-SB-A	NA				
2L-1-SB-B	25.8	0.0652	0.5654	22.6	
2L-1-SB-C	40.7	0.0327	0.2408	9.6	0.2204
2L-1-SB-D	60.9	0.0129	0.0399	1.6	
2L-1-AX-A	24.8	0.0931	0.8429	33.7	
2L-1-AX-B	30.4	0.0527	0.4408	17.6	
2L-1-AX-C	43.3	0.0290	0.2035	8.1	0.1751
2L-1-AX-D	58.0	0.0147	0.0587	2.3	
2L-1-COR-A	26.4	0.0732	0.6448	25.8	
2L-1-COR-B	37.0	0.0388	0.3021	12.1	
2L-1-COR-C	56.2	0.0160	0.0717	2.9	
2L-1-COR-D	60.9	0.0129	0.0399	1.6	
2L-1-DCI-A	NA				
2L-1-DCI-B	27.6	0.0600	0.5135	20.5	
2L-1-DCI-C	46.1	0.0255	0.1680	6.7	
2L-1-DCI-D	60.2	0.0133	0.0442	1.8	

Table C-4 Pretreatment Chloride Contents

Corrosion Inhibitor Evaluation		SHRP C-103 CHLORIDE CONTENTS		PROBE: A	DATE: 6/23/91
Specimen	Measured mV	Measured % Cl	Predicted % Cl	Predicted lbs/cy	Standard % Cl
2L-1-SB-A	20.7	0.0826	0.7380	29.5	
2L-1-SB-B	32.1	0.0487	0.4010	16.0	
2L-1-SB-B	46.8	0.0247	0.1597	6.4	
2L-1-SB-B	61.2	0.0127	0.0380	1.5	
2L-1-AX-A	20.4	0.0837	0.7494	30.0	
2L-1-AX-B	31.4	0.0503	0.4170	16.7	
2L-1-AX-C	44.7	0.0272	0.1851	7.4	
2L-1-AX-D	59.2	0.0139	0.0506	2.0	0.0473
2L-1-COR-A	NA				
2L-1-COR-B	27.3	0.0608	0.5219	20.9	
2L-1-COR-C	48.6	0.0227	0.1399	5.6	
2L-1-COR-D	62.7	0.0118	0.0293	1.2	
2L-0-LMC-A	25.6	0.1039	0.9498	38.0	
2L-0-LMC-B	27.3	0.0608	0.5219	20.9	
2L-0-LMC-C	38.7	0.0359	0.2726	10.9	
2L-0-LMC-D	58.0	0.0147	0.0587	2.3	
2M-1LMC-A	21.1	0.0811	0.7229	28.9	
2M-1LMC-B	31.2	0.0508	0.4217	16.9	0.3681
2M-1LMC-C	41.5	0.0315	0.2288	9.2	
2M-1LMC-D	57.0	0.0154	0.0658	2.6	
2L-BC-A	25.0	0.0677	0.5899	23.6	
2L-BC-A	33.4	0.0459	0.3725	14.9	
2L-BC-A	50.7	0.0206	0.1186	4.7	
2L-BC-A	61.8	0.0123	0.0345	1.4	
2L-TP-A	NA				
2L-TP-B	31.4	0.0503	0.4170	16.7	
2L-TP-C	47.9	0.0235	0.1474	5.9	
2L-TP-D	60.2	0.0133	0.0442	1.8	

Table C-4 Pretreatment Chloride Contents

Corrosion Inhibitor Evaluation		SHRP C-103 CHLORIDE CONTENTS			PROBE: B
					DATE: 8/9/91
Specimen	Measured mV	Measured % Cl	Predicted % Cl	Predicted lbs/cy	Standard % Cl
1M-CON-A	27.6	0.0651	0.5642	22.6	
1M-CON-B	34.9	0.0473	0.3866	15.5	
1M-0-LMC-A	27.9	0.0642	0.5558	22.2	
1M-0-LMC-B	33.3	0.0507	0.4208	16.8	
1M-1-DCI-A	31.3	0.0554	0.4672	18.7	
1M-1-DCI-B	38.3	0.0407	0.3211	12.8	
1M-1-SB-A	30.4	0.0576	0.4894	19.6	
1M-1-SB-B	36.4	0.0443	0.3565	14.3	
1M-1-AX-A	27.6	0.0651	0.5642	22.6	
1M-1-AX-B	33.6	0.0501	0.4142	16.6	
1M-1-COR-A	29.5	0.0599	0.5125	20.5	
1M-1-COR-B	37.9	0.0415	0.3283	13.1	
1LM-0-LMC-	29.0	0.0612	0.5257	21.0	
1LM-0-LMC-B	40.6	0.0368	0.2820	11.3	
1LM-0-LMC-C	51.0	0.0234	0.1464	5.9	
1LM-0-LMC-	62.6	0.0141	0.0521	2.1	
1LM-1-DCI-A	27.6	0.0651	0.5642	22.6	
1LM-1-DCI-B	34.3	0.0485	0.3991	16.0	
1LM-1-DCI-C	43.9	0.0319	0.2322	9.3	
1LM-1-DCI-D	55.8	0.0189	0.1016	4.1	
1LM-1-SB-A	29.1	0.0610	0.5230	20.9	
1LM-1-SB-B	41.7	0.0351	0.2646	10.6	
1LM-1-SB-C	51.9	0.0225	0.1373	5.5	
1LM-1-SB-D	63.4	0.0136	0.0472	1.9	
1LM-1-AX-A	32.9	0.0516	0.4298	17.2	
1LM-1-AX-B	44.1	0.0316	0.2294	9.2	
1LM-1-AX-C	59.2	0.0163	0.0751	3.0	
1LM-1-AX-D	66.7	0.0117	0.0285	1.1	

Table C-4 Pretreatment Chloride Contents

Corrosion Inhibitor Evaluation		SHRP C-103 CHLORIDE CONTENTS			PROBE: B
					DATE: 8/9/91
Specimen	Measured mV	Measured % Cl	Predicted % Cl	Predicted lbs/cy	Standard % Cl
1LM-1-COR-	28.7	0.0620	0.5338	21.4	
1LM-1-COR-B	39.1	0.0393	0.3071	12.3	
1LM-1-COR-C	48.5	0.0261	0.1737	6.9	
1LM-1-COR-	61.5	0.0148	0.0592	2.4	

Table C-5. Chloride Content, 333 Days After Treatment

Corrosion Inhibitor Evaluation		SHRP C-103 CHLORIDE CONTENTS			PROBE: A
					DATE: 4/25/92
Specimen	Measured mV	Measured % Cl	Predicted % Cl	Predicted lbs/cy	Standard % Cl
2L-0-LMC-A	64.7	0.0155	0.1251	5.0	
2L-0-LMC-B	100.8	0.0034	0.0037	0.1	
2L-0-LMC-C	98.3	0.0038	0.0075	0.3	
2L-0-LMC-D	86.1	0.0063	0.0328	1.3	
1H-D0-LMCA	54.8	0.0236	0.2057	8.2	
1H-D0-LMCB	83.5	0.0070	0.0401	1.6	
1H-D0-LMCC	53.5	0.0249	0.2190	8.8	
1H-D0-LMCD	44.4	0.0366	0.3357	13.4	
1H-D1-DCI-D	51.4	0.0272	0.2421	9.7	
1H-D1-SB-D	51.5	0.0271	0.2409	9.6	
1H-D1-AX-D	43.8	0.0375	0.3451	13.8	
1H-D1-COR-	43.1	0.0386	0.3564	14.3	

Continued

Table C-5. Chloride Content, 333 Days After Treatment

Corrosion Inhibitor Evaluation		SHRP C-103 CHLORIDE CONTENTS		PROBE: A	
				DATE: 4/25/92	
Specimen	Measured mV	Measured % Cl	Predicted % Cl	Predicted lbs/cy	Standard % Cl
1L-D1-DCI-A	24.9	0.0834	0.8036	32.1	
1L-D1-DCI-B	36.0	0.0522	0.4915	19.7	
1L-D1-DCI-C	58.9	0.0198	0.1682	6.7	
1L-D1-DCI-D	71.0	0.0119	0.0889	3.6	
1L-D1-SB-A	33.0	0.0592	0.5620	22.5	
1L-D1-SB-B	45.5	0.0349	0.3191	12.8	
1L-D1-SB-C	66.8	0.0142	0.1119	4.5	
1L-D1-SB-D	94.2	0.0045	0.0146	0.6	
1L-D1-AX-A	39.1	0.0458	0.4275	17.1	
1L-D1-AX-B	47.9	0.0315	0.2854	11.4	
1L-D1-AX-C	67.4	0.0138	0.1084	4.3	
1L-D1-AX-D	85.9	0.0063	0.0333	1.3	
1L-D1-COR-A	32.5	0.0605	0.5747	23.0	
1L-D1-COR-B	44.6	0.0363	0.3326	13.3	
1L-D1-COR-C	52.2	0.0263	0.2330	9.3	
1L-D1-COR-D	61.9	0.0175	0.1446	5.8	
1L-D0-LMC-A	30.9	0.0647	0.6170	24.7	
1L-D0-LMC-B	46.4	0.0336	0.3061	12.2	
1L-D0-LMC-C	NA				
1L-D0-LMC-D	82.2	0.0074	0.0440	1.8	
1L-AX-DCI-A	35.2	0.0539	0.5095	20.4	
1L-AX-DCI-B	43.0	0.0388	0.3580	14.3	
1L-AX-DCI-C	61.1	0.0181	0.1506	6.0	
1L-AX-DCI-D	86.2	0.0063	0.0325	1.3	
1L-AX-COR-	32.0	0.0618	0.5876	23.5	
1L-AX-COR-	45.2	0.0354	0.3236	12.9	
1L-AX-COR-	55.4	0.0230	0.1998	8.0	
1L-AX-COR-	69.9	0.0125	0.0945	3.8	
1H-AX-LMC-	33.9	0.0570	0.5399	21.6	
1H-AX-LMC-	41.8	0.0408	0.3782	15.1	

Table C-6. ASTM C666 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing

P = Relative Dynamic Modulus of Elasticity

Specimen	Initial Reading		4/2/92, 24 cycles		4/6/92, 49 cycles		4/15/92, 100 cycles		P(100)
	Flex. (KHz)	Long. (KHz)	Flex. (KHz)	Long. (KHz)	Flex. (KHz)	Long. (KHz)	Flex. (KHz)	Long. (KHz)	
DCI-M4-1	2.199	1.745	2.028	1.613	1.471	1.081	0.397	1.670	3.3
DCI-M4-2	2.209	1.729	2.148	1.677	1.770	1.379	0.866	0.858	15.4
COR-M1-1	2.285	1.820	2.253	1.800	2.260	1.800	2.260	1.810	97.8
COR-M1-2	2.275	1.796	2.253	1.778	2.256	1.780	2.260	1.790	98.7
COR2-1	2.274	1.787	2.262	1.774	2.251	1.772	2.250	1.780	97.9
COR2-2	2.277	1.793	2.252	1.783	2.250	1.772	2.250	1.780	97.6
COR-M4-1	2.234	1.763	2.218	1.751	2.223	1.763	2.220	1.770	98.8
COR-M4-2	2.267	1.791	2.252	1.782	2.253	1.782	2.260	1.800	99.4

Specimen	Initial Reading		4/15/92, 51 cycles		5/4/92, 149 cycles		5/27/92, 265 cycles		P(49)
	Flex. (KHz)	Long. (KHz)	Flex. (KHz)	Long. (KHz)	Flex. (KHz)	Long. (KHz)	Flex. (KHz)	Long. (KHz)	
Normal-1	2.322	1.819	2.310	1.800	2.310	1.820	2.340	1.820	101.6
Normal-1	2.268	1.780	2.230	1.780	2.280	1.790	2.290	1.790	101.9

Specimen	Initial Reading		5/4/92, 100 cycles		5/27/92, 225 cycles		P(24)
	Flex. (KHz)	Long. (KHz)	Flex. (KHz)	Long. (KHz)	Flex. (KHz)	Long. (KHz)	
LMC-1	2.120	1.710	2.190	1.730	2.200	1.750	107.7

Table C-6. ASTM C666 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
P = Relative Dynamic Modulus of Elasticity

Specimen	5/4/92 200 cycles		5/27/92 315 cycles	
	Flex. (KHz)	Long. (KHz)	Flex. (KHz)	Long. (KHz)
DCI-M4-1	NA	NA	NA	NA
DCI-M4-2	NA	NA	NA	NA
COR-M1-1	2.280	1.830	2.310	1.830
COR-M1-2	2.270	1.800	2.280	1.800
COR2-1	2.280	1.780	2.290	1.800
COR2-2	2.290	1.790	2.290	1.800
COR-M4-1	2.260	1.790	2.260	1.800
COR-M4-2	2.280	1.820	2.310	1.820
		P(100)		P(100)
		NA		NA
		99.6		102.2
		99.6		100.4
		100.5		101.4
		101.1		101.1
		102.3		102.3
		101.2		103.8

Table C-7. ASTM C-666 Resistance of Concrete to Rapid Freezing and Thawing
Elastic Modulus Determination
March 28, 1992

Specimen	Length (mm)	Height (mm)	Width (mm)	Mass (kg)	Density (g/cm ³)	Poisson's Ratio EF,G	EL,G
DCI-M4-1	401.0	104.0	77.0	7.08	2.205	0.28	0.03
DCI-M4-2	401.0	105.0	76.5	7.06	2.192	0.27	0.03
COR-M1-1	401.0	103.0	77.0	7.17	2.254	0.26	0.03
COR-M1-2	401.0	103.0	76.0	7.16	2.281	0.29	0.03
COR2-1	401.0	103.0	76.0	7.10	2.262	0.28	0.03
COR2-2	401.0	103.0	76.0	7.10	2.262	0.26	0.03
COR-M4-1	401.0	103.0	75.0	6.99	2.256	0.23	0.03
COR-M4-2	401.0	103.0	77.0	7.11	2.236	0.27	0.03

Specimen	Flex. (KHz)	Long. (KHz)	Tors. (KHz)	Flex. (msi)	Long. (ksi)	Tors. (msi)
DCI-M4-1	2.199	1.745	2.728	5.06	633	1.98
DCI-M4-2	2.209	1.729	2.713	5.00	618	1.96
COR-M1-1	2.285	1.820	2.876	5.65	704	2.24
COR-M1-2	2.275	1.796	2.831	5.68	693	2.21
COR2-1	2.274	1.787	2.839	5.62	681	2.20
COR2-2	2.277	1.793	2.862	5.62	685	2.24
COR-M4-1	2.234	1.763	2.818	5.38	661	2.18
COR-M4-2	2.267	1.791	2.851	5.51	676	2.18

Table C-8.

Alox Slab
 January 4, 1992
 77 Days prior to treatment

CSE Potentials

-mV	A	B	C
1	370	318	337
2	336	290	328
3	276		
4	291		

Mean = 318
 STD = 31.1

3LP Icorr Readings

mA/sqft	A	B	C
1	1.49	1.14	1.49
2	0.89	1.09	1.55
3	0.81		
4			1.77

Mean = 1.28
 STD = 0.35

Geocisa Icorr Readings

uA/sqcm	A	B	C
1	0.068	0.061	0.077
2	0.076		
3			
4			

Mean = 0.071
 STD = 0.008

Table C-8. Alox Slab
 January 31, 1992
 50 Days prior to treatment

CSE Potentials

-mV	A	B	C
1	353	288	322
2	313	269	313
3	262		
4	281		

Mean = 300
 STD = 30.6

3LP Icorr Readings

mA/sqft	A	B	C
1	1.06	1.16	1.06
2	1.19	1.17	1.30
3	0.98		
4	1.41		

Mean = 1.16
 STD = 0.14

Geocisa Icorr Readings

uA/sqcm	A	B	C
1	0.077	0.064	0.048
2	0.072	0.068	0.100
3	0.085		
4			

Mean = 0.073
 STD = 0.016

Table C-8. DCI Slab
 January 4, 1992
 54 Days prior to treatment

CSE Potentials

-mV	A		B
1	335	355	310
2	359	332	284
3	378	314	
4	380	326	294
5	390	349	318
6	367	359	331
7	374	335	340

Mean = 342
 STD = 29.1

3LP Icorr Readings

mA/sqft	A		B
1	2.25	1.81	1.77
2	2.33	2.16	1.58
3	2.78	2.46	1.45
4	3.17	2.04	2.32
5	2.52	2.65	2.62
6	2.72	3.08	2.55
7	2.06	2.50	2.40

Mean = 2.34
 STD = 0.45

Table C-8.
Continued

DCI Slab
January 4, 1992
54 Days prior to treatment

Geocisa Icorr Readings

uA/sq.cm	A	B	
1			
2	0.073	0.129	
3	0.071	0.081	
4	0.102	0.092	0.091
5	0.075	0.106	0.150
6	0.204	0.106	0.109
7			

Mean = 0.107
STD = 0.037

Table C-8. DCI Slab
 January 31, 1992
 27 Days prior to treatment

CSE Potentials

-mV	A		B
1	293	321	290
2	311	320	289
3	332	314	295
4	346	323	295
5	363	340	298
6	338	339	315
7	351	323	316

Mean = 320
 STDS = 21.5

3LP Icorr Readings

mA/sqft	A		B
1	1.63	2.05	2.11
2	2.02	2.58	2.16
3	2.19	2.33	2.03
4	2.29	2.34	2.59
5	2.30	2.30	2.50
6	2.34	3.10	2.24
7	2.16	2.12	1.89

Mean = 2.25
 STDS = 0.30

Table C-8.
Continued

DCI Slab
January 31, 1992
20 Days prior to treatment

Geocisa Icorr Readings

uA/sq.cm	A	B
1		0.064
2	0.188	0.085
3	0.137	0.145
4	0.292	0.085
5	0.165	0.165
6	0.375	0.125
7	0.141	

Mean = 0.164
STDS = 0.093

Table C-8. Cortec Slab
 January 4, 1992
 70 Days prior to treatment

CSE Potentials

-mV	A	B
1	259	237
2	249	229
3	242	251
4	268	251
5	294	251
6	282	279
7	349	256

Mean = 260
 STD = 27.4

3LP Icorr Readings

mA/sqft	A	B
1	1.30	1.71
2	0.91	1.64
3	1.25	1.96
4	1.20	1.31
5	1.01	1.27
6	1.14	1.21
7	1.89	1.29

Mean = 1.31
 STD = 0.27

Table C-8.
Continued

Cortec Slab
January 4, 1992
70 Days prior to treatment

Geocisa Icorr Readings

uA/sq.cm		A	B
1		0.246	
2	0.115	0.165	0.097
3	0.113	0.292	0.139
4	0.116	0.167	0.084
5	0.094	0.108	0.062
6	0.085	0.139	0.111
7		0.137	0.102

Mean = 0.132

STD = 0.057

Table C-8. Cortec Slab
 January 30, 1992
 44 Days prior to treatment

CSE Potentials

-mV	A	B
1	190	174
2	180	177
3	179	197
4	190	185
5	208	179
6	190	207
7	248	176

Mean = 191
 STD = 16.6

3LP Icorr Readings

mA/sqft	A	B
1	1.73	1.55
2	1.25	1.45
3	1.22	1.20
4	1.38	1.61
5	1.48	1.56
6	1.17	1.40
7	0.96	1.50

Mean = 1.35
 STD = 0.20

Table C-8.
Continued

Cortec Slab
January 30, 1992
44 Days prior to treatment

Geocisa Icorr Readings

uA/sq.cm	A	B
1	0.126	
2	0.155	0.188
3	0.165	0.173
4	0.133	0.231
5	0.145	0.085
6	0.145	0.153
7	0.154	0.435

Mean = 0.169
STD = 0.071

Table C-9. DCI Slab
 March 26, 1992
 36 Days after treatment

CSE Potentials

-mV	A		B
1	239	197	213
2	224	210	215
3	234	226	215
4	236	253	227
5	235	237	204
6	255	240	215
7	265	245	211

Mean = 228
 STD = 17.9

3LP Icorr Readings

mA/sqft	A		B
1	3.40	3.84	3.98
2	3.49	3.78	3.64
3	4.29	4.20	3.21
4	4.38	4.76	4.44
5	4.70	5.37	3.99
6	5.14	4.34	3.44
7	4.08	4.31	2.90

Mean = 4.08
 STD = 0.62

Table C-9. DCI Slab
 Continued March 26, 1992
 36 Days after treatment

Geocisa Icorr Readings

uA/sq.cm	A		B
1	0.799	0.194	0.179
2	0.991	0.543	0.199
3	0.242	0.344	0.161
4	0.237	0.196	0.106
5	0.235	0.273	0.251
6	0.524	0.242	0.177
7	0.208	0.277	0.247

Mean = 0.315

STD = 0.222

Table C-9. Alox Slab
 April 24, 1992
 34 Days after treatment

CSE Potentials

-mV	A	B	C
1	270	272	288
2	267	274	286
3	266	278	280
4	274	280	242

Mean = 273
 STD = 12.0

3LP Icorr Readings

mA/sqft	A	B	C
1	3.51	3.44	2.75
2	2.73	3.31	3.00
3	3.10	2.57	3.25
4	3.07	3.16	1.45

Mean = 2.94
 STD = 0.55

Geocisa Icorr Readings

uA/sqcm	A	B	C
1	0.067	0.049	0.047
2	0.050	0.059	0.066
3	0.054	0.065	0.061
4	0.037	0.070	0.061

Mean = 0.057
 STD = 0.010

Table C-9. Cortec Slab
 April 24, 1992
 40 Days after treatment

CSE Potentials

-mV	A	B
1	114	127
2	121	130
3	125	124
4	143	139
5	144	144
6	151	152
7	168	158

Mean = 138
 STD = 13.3

3LP Icorr Readings

mA/sqft	A	B
1	0.93	1.00
2	1.01	1.12
3	1.12	1.02
4	1.18	1.12
5	1.03	1.11
6	1.21	1.05
7	1.07	1.01

Mean = 1.10
 STD = 0.10

Table C-9.
Continued

Cortec Slab
April 24, 1992
40 Days after treatment

Geocisa Icorr Readings

uA/sq.cm	A	B	
1	0.025	0.034	0.024
2	0.014	0.036	0.056
3	0.034	0.045	0.034
4	0.042	0.060	0.037
5	0.027	0.033	0.038
6	0.026	0.039	0.034
7	0.024	0.020	0.046

Mean = 0.042

STD = 0.034

Table C-9. DCI Slab
 April 24, 1992
 65 Days after treatment

CSE Potentials

-mV	A		B
1	245	241	231
2	232	233	234
3	235	232	234
4	247	249	237
5	247	253	239
6	264	260	241
7	265	256	240

Mean = 244
 STD = 10.8

3LP Icorr Readings

mA/sqft	A		B
1	4.57	4.54	4.16
2	4.24	4.31	4.55
3	4.52	4.58	3.87
4	4.30	4.34	4.29
5	4.40	4.75	5.12
6	5.51	5.10	4.44
7	3.95	4.10	3.99

Mean = 4.46
 STD = 0.40

Table C-9. DCI Slab
 Continued April 24, 1992
 65 Days after treatment

Geocisa Icorr Readings

uA/sq.cm	A	B
1	0.321	0.433
2		0.418
3	0.220	0.355
4	0.311	0.483
5	0.239	0.448
6	0.345	0.291
7	0.344	0.255

Mean = 0.329
 STD = 0.089

Table C-10. Alox Slab
 May 12, 1992
 52 Days after treatment

CSE Potentials

-mV	A	B	C
1	266	174	247
2	267	210	235
3	256	227	248
4	222	233	215

Mean = 233
 STD = 26.4

3LP Icorr Readings

mA/sqft	A	B	C
1	2.20	2.05	2.17
2	1.84	2.61	2.15
3	2.12	2.71	3.12
4	1.87	2.30	2.30

Mean = 2.29
 STD = 0.37

Geocisa Icorr Readings

uA/sqcm	A	B	C
1	0.068		0.051
2	0.061	0.061	0.078
3	0.075	0.093	0.073
4	0.061	0.108	0.090

Mean = 0.074
 STD = 0.017

Table C-10. Cortec Slab
 May 12, 1992
 58 Days after treatment

CSE Potentials

-mV	A	B
1	98	124
2	119	120
3	120	116
4	130	125
5	137	132
6	142	141
7	159	138

Mean = 125
 STD = 13.3

3LP Icorr Readings

mA/sqft	A	B
1	1.06	1.22
2	1.12	1.15
3	1.33	1.26
4	1.26	1.32
5	1.21	1.26
6	1.11	1.25
7	1.19	1.07

Mean = 1.20
 STD = 0.11

Table C-10. Cortec Slab
 Continued May 12, 1992
 58 Days after treatment

Geocisa Icorr Readings

uA/sq.cm	A	B
1	0.016	0.056
2	0.034	0.053
3	0.088	0.061
4	0.068	0.042
5	0.046	0.040
6	0.044	0.028
7	0.030	0.050

Mean = 0.058
 STD = 0.034

Table C-10. DCI Slab
 May 12, 1992
 83 Days after treatment

CSE Potentials

-mV	A		B
1	237	222	227
2	235	216	220
3	236	225	227
4	242	228	228
5	243	237	226
6	257	242	217
7	259	248	220

Mean = 233
 STD = 12.3

3LP Icorr Readings

mA/sqft	A		B
1	2.74	3.63	3.23
2	3.04	4.07	3.30
3	3.17	3.37	3.29
4	3.05	3.46	3.26
5	3.06	4.05	3.84
6	3.84	4.43	3.31
7	3.06	3.43	2.70

Mean = 3.40
 STD = 0.44

Table C-10. DCI Slab
 Continued May 12, 1992
 83 Days after treatment

Geocisa Icorr Readings

uA/sq.cm	A	B
1	0.525	0.166
2	0.221	0.174
3	0.149	0.185
4	0.185	0.243
5	0.200	0.175
6	0.236	0.131
7	0.210	0.127

Mean = 0.201
 STD = 0.082

Appendix D

Constuction Specifications

**RECOMMENDED SPECIAL TECHNICAL PROVISIONS
FOR JOB SPECIFICATIONS**

Note: The specifications are not to be considered all inclusive of quality control testing specifications, rather they represent guidelines for materials and application.

1. PROCEDURE

General: Treatment of bridge decks with surface applied corrosion inhibitors and inhibitor modified overlays shall consist of the following steps in the order presented:

- 1.1 Scarification of the deck surface.
- 1.2 Application of surface applied corrosion inhibitors.
- 1.3 Surface preparation.
- 1.4 Overlay application.

2. SCARIFICATION

2.1 General: The cover concrete shall be removed to the level of the reinforcing steel for the area to be treated. Any unsound concrete shall be removed to a depth of $1 \frac{1}{2}$ times the maximum aggregate size below the reinforcing steel.

2.2 Scarification Details

2.2.1 Area of deck to be scarified = ____ sq. ft. (n.b.: insert appropriate value)

2.2.2 Depth of scarification = ____ in. (n.b.: insert appropriate value) If steel reinforcement is encountered, the scarification depth at such locations shall be to the top of the reinforcing bars.

2.3 Cleanup: Following scarification, the surface of the bridge deck in the area to be treated shall be cleaned to remove particulate matter and fines. Water must not be allowed to contact the deck after the cover concrete is removed and should not be used for this process. Should water wet the

scarified area prior to the application of the corrosion inhibitors, the concrete surface shall be dried for a period of 30 minutes with a propane fired infrared heater using a surface temperature of 400°F. Spray application of the inhibitors shall be delayed until the concrete has returned to ambient temperature.

2.4 Patching: Delaminated and other deteriorated concrete areas shall be patched with a concrete containing the appropriate corrosion inhibitor. Prior to patching the exposed reinforcing steel shall be shotblasted or sandblasted to near white metal.

2.4.1 For DCI, the dosage shall be 6 gallons / yd³.

2.4.2 For Cortec 2000, the dosage shall be 2 pints / yd³.

3. APPLICATION OF SURFACE APPLIED CORROSION INHIBITOR

3.1 General: Application of the surface applied inhibitor involves spraying the dry concrete with a liquid corrosion inhibitor. The inhibitor is to soak into the base concrete prior to overlay.

3.2 Corrosion Inhibitor

3.2.1 Corrosion inhibitor to be applied (see inserts)

3.2.2 Supplier (see inserts)

3.2.3 Solvent to be mixed with corrosion inhibitor to produce desired concentration (see inserts)

3.2.4 Desired concentration (see inserts)

3.2.5 Application Rate (see inserts) The inhibitor can be successfully applied with an industrial grade garden sprayer.

3.2.6 A total of three applications of the inhibitor are to be applied. (see inserts for intervals)

3.3 Safety in Handling and Storing the Inhibitor

See inserts.

- 3.4 Weather Protection: Provisions must be made to prevent precipitation runoff from contacting the surface of the deck during the inhibitor application.

4. SURFACE PREPARATION

- 4.1 General: Prior to overlay the deck surface must be lightly shotblasted or sandblasted to remove any residues left by the inhibitors. This must be done to ensure adequate bond between the substrate concrete and the overlay.
- 4.2 Shotblasting or Sandblasting: The concrete surface of the deck to be treated shall be lightly blasted with shot or sand to remove any oily or greasy residues left by the inhibitor.
- 4.3 Cleanup: Following the completion of shot or sandblasting, the treated surface of the bridge deck shall be cleaned to remove particulate matter and fines.

5. OVERLAY PLACEMENT

- 5.1 General: The deck shall be overlaid with inhibitor modified concrete with the specified cover depth.
- 5.2 Materials
- 5.2.1 Concrete batch specifications suitable for deck overlays will be supplied by the contracting officer.
- 5.2.2 The corrosion inhibitor (see inserts) will be added as an admixture at the batch plant
- 5.2.3 Properties of overlay concrete: The inhibitor modified concrete shall have the following properties:
- (a) Air Content: $7 \frac{1}{2}\% \pm 1\%$
- (b) 28-day compressive strength: equal to or greater than _____ psi. (n.b.: insert appropriate value)

5.3 Placement: The overlay shall be placed following standard practice. A thick concrete grout, containing the inhibitor, shall be applied to the substrate immediately prior to overlay. The grout shall not be allowed to dry or set before the overlay is placed. The overlay shall be moist cured for a period of 3 days after placement. In addition to standard quality control procedures, bond strength tests shall be run in accordance with ACI 503R. Failure of a section of the overlay to meet minimum bond strength requirements shall result in the removal and replacement of that section.

**Insert Set I.
Cortec 2020 and 2000**

- 3.2.1 Cortec 2020 is a water based inhibitor to be used as a surface treatment or by injection.
- 3.2.2 The product can be obtained from:
Cortec Corporation
St. Paul, MN 55107
(612)-224-5643
- 3.2.3 None.
- 3.2.4 Cortec 2020 is packaged at the desired application concentration by the manufacturer.
- 3.2.5 Each application of Cortec 2020 shall be spray applied at the rate of 225 ft² / gallon. The inhibitor can be successfully applied with a Hudson type industrial sprayer.
- 3.2.6 A total of three applications of the inhibitor are to be applied at 2, and 12 hours after the initial application.

3.3 Safety and Handling of the Inhibitor

- 3.3.1 General: The inhibitor must be stored, handled and applied in such a manner as to prevent fire, and injurious exposure to personnel associated with the job and to the public. A material data form covering the hazardous characteristics of the inhibitor appears in Exhibit 1. Unsafe handling practice will be sufficient cause to discontinue work until the hazardous procedures are corrected. The handling and use of the inhibitor shall in all cases comply with the requirements of applicable Federal, State, and local safety requirements and ordinances.

3.3.2 Inhibitor Storage: The inhibitor should be stored in original shipping containers. Containers should be kept tightly closed and kept away from heat, open flame, and spark sources.

3.3.3 Personnel Protection: Personnel working with the inhibitor shall be provided with and use safety glasses or goggles, NIOSH approved respirator, and Chemical resistant rubber or plastic gloves. The contractor shall provide a field eye wash and safety shower to be used in the event of an accidental splash of inhibitor on the workers. Additionally worker shall be required to thoroughly wash hands with soap and water prior to eating, smoking, drinking, or using the lavatory.

3.3.4 Accidental Spills of the Inhibitor: Accidental spills should be absorbed on sweeping compound or other absorbent material. The compound may be incinerated or disposed of in accordance to existing Federal, State and Local environmental regulations.

3.4 Weather Protection: See general notes.

5.2.2 Cortec 2000 will be added to the overlay concrete at the rate of 2 lb per cubic yard of concrete at the batch plant.

Insert Set II., DCI

- 3.2.1 DCI is a water based inhibitor containing 30% by weight calcium nitrite to be used as a surface treatment or concrete admixture.
- 3.2.2 The product and technical assistance can be obtained from:
- Neil Berke
Construction Products Division
W.R. Grace and Company
62 Whittemore Ave
Cambridge, MA 02140
(617) 876-1400 Extension 3155
- 3.2.3 Ordinary tap water is used for dilution of the product to the application concentration.
- 3.2.4 The inhibitor is to be applied at a concentration of 15% by weight calcium nitrite. This concentration may be obtained by mixing equal parts DCI and water.
- 3.2.5 Each application of the DCI solution shall be spray applied at the rate of 150 ft² / gallon. The inhibitor can be successfully applied with a Hudson type industrial sprayer.
- 3.2.6 A total of three applications of the inhibitor are to be applied at 1 and 8 hours after the initial application.

3.3 Safety and Handling of the Inhibitor

- 3.3.1 General: The inhibitor must be stored, handled, and applied in such a manner to prevent injurious exposure to personnel associated with the job and to the public. A material data form covering the hazardous characteristics of the inhibitor appears in Exhibit 2. The handling and use of the inhibitor shall

in all cases comply with the requirements of applicable Federal, State and Local safety requirements and ordinances.

3.3.2 Personnel Protection: Personnel working with the inhibitor shall be provided with and use safety glasses or goggles, and rubber or other impervious gloves. Additional appropriate clothing should be worn to minimize skin contact.

3.3.3 Accidental Spills of the Inhibitor: Spills should be absorbed with an inert, non-combustible media and removed for disposal in accordance with existing Federal, State, and Local environmental regulations. Spills should be prevented from entering drinking water supplies and streams.

3.4 Weather Protection: See general notes.

5.2.2 DCI will be added as an admixture to the overlay concrete at the rate of 6 gallons / cubic yard of concrete at the batch plant. DCI acts as a set accelerator and requires the following additional admixtures:

(a) Darasen 100 or other approved ASTM C 494 Type G high range water reducer to be added at the rate of 12 oz / 100 lbs cement.

(b) Daratard-17 or other approved ASTM C 494 Type B & D initial set retarder to be added at the rate of 6 oz / 100 lbs cement.

These addition rates are presented as guidelines. Trial batches should be constructed to ensure proper workability and set time.

Insert Set III., Alox 901

- 3.2.1 Alox 901 is an oxygenated hydrocarbon to be used as a surface treatment.
- 3.2.2 The product can be obtained from:
- Alox Corporation
3943 Buffalo Ave.
P.O. Box 517
Niagara Falls, NY 14302
(716) 282-1295
- 3.2.3 Denatured ethyl alcohol is used as a solvent to obtain the inhibitor solution.
- 3.2.4 The inhibitor is applied at a concentration of 4.7% by weight Alox 901 in denatured ethyl alcohol. The inhibitor must be field mixed at the job site.
- 3.2.5 Each application of Alox 901 shall be spray applied at the rate of 70 ft² / gallon. The inhibitor can be successfully applied with an Hudson type industrial sprayer.
- 3.2.6 A total of three applications of the inhibitor are to be applied at 1, and 4 hours after the initial application.

3.3 Safety and Handling of the Inhibitor

- 3.3.1 General: The inhibitor must be stored, handled and applied in such a manner as to prevent fire, explosion, and injurious exposure to personnel associated with the job and to the public. A material data form covering hazardous characteristics of the inhibitor appears in Exhibit 3. Unsafe handling practices will be sufficient cause to discontinue work until the hazardous procedures are corrected. The handling and use of the inhibitor shall in all cases comply with

the requirements of applicable Federal, State, and Local safety requirements and ordinances.

- 3.3.2 Storage of Inhibitor Materials: The Alox 901 and denatured ethyl alcohol shall be stored in original shipping containers prior to application. Maximum alcohol storage temperature shall not exceed 90°F (32°C). The storage facility shall be constructed in such a fashion as to provide protection from direct sunlight, fire hazard, and oxidizing chemicals. Sufficient ventilation shall be maintained in the storage facility to prevent the hazardous buildup of alcohol vapor concentrations in the storage air space. "Warning" and "No Smoking" signs shall be placed at appropriate intervals.
- 3.3.3 Fire Protection: Four 20-lb nontoxic, dry chemical fire extinguishers meeting Underwriters Laboratories, Inc. approval for Class A, B, and C fires, with a minimum rating of 20 A, 80 B, C shall be furnished by the contractor and kept near the alcohol storage area.
- 3.3.4 Personnel Protection: Personnel working with the inhibitor shall be provided with and use safety eyeglasses or goggles, and oil impervious gloves.
- 3.3.5 Accidental Spills of the Inhibitor: The inhibitor must be prevented from entering streams and waterways. Attempt to recover and recycle accidental spills, non-recyclable spills should be absorbed with vermiculite or dry sawdust, cleaned up with non-sparking tools, and disposed of by methods such as incineration complying with government regulations.

3.4 Mixing of Inhibitor and Denatured Alcohol: The Alox 901 shall be mixed with the denatured ethyl alcohol to the specified concentration prior to application. Mixing shall be accomplished by using electric-motor-driven (explosion proof), propeller type stirrers.

3.5 Weather Protection: See 3.4 in general notes.

5.2.2 No corrosion inhibitor of any type will be added to the overlay concrete unless specified by the engineer.

**RECOMMENDED SPECIAL TECHNICAL PROVISIONS
FOR JOB SPECIFICATIONS**

Note: The following specifications are adapted in part from the Commonwealth of Pennsylvania, Department of Transportation Report on Research Project No. 83-5B, "Deep Polymer Impregnation of a Bridge Deck Using the Grooving Technique," by P.D. Cady and R.E. Weyers. The specifications are not to be considered all inclusive of quality control testing specifications, rather they represent guidelines for materials and application.

1. PROCEDURE

General: Treatment of dried bridge decks with surface applied corrosion inhibitors and inhibitor modified overlays shall consist of the following steps in the order presented:

- 1.1 Scarification of the deck surface.
- 1.2 Drying of the concrete deck.
- 1.3 Application of surface applied corrosion inhibitors.
- 1.4 Surface preparation.
- 1.5 Overlay application.

2. SCARIFICATION

2.1 General: The cover concrete shall be removed to the level of the reinforcing steel for the area to be treated. Any unsound concrete shall be removed to a depth of $1\frac{1}{2}$ times the maximum aggregate diameter below the reinforcing steel.

2.2 Scarification Details

- 2.2.1 Area of deck to be scarified = _____ sq. ft. (n.b.: insert appropriate value)
- 2.2.2 Depth of scarification = _____ in. (n.b.: insert appropriate value) If steel reinforcement is encountered, the scarification depth at such locations shall be to the top of the reinforcing bars.

- 2.3 Cleanup: Following scarification, the surface of the bridge deck in the area to be treated shall be cleaned to remove particulate matter and fines. Water must not be allowed to contact the deck after the cover concrete is removed and should not be used for this process.
- 2.4 Patching: Delaminated and other deteriorated concrete areas shall be patched with a concrete containing the appropriate corrosion inhibitor. Prior to patching exposed reinforcing steel shall be shotblasted or sandblasted to near white metal.
- 2.4.1 For DCI, the dosage shall be 6 gallons / yd³.
- 2.4.2 For Cortec 2000, the dosage shall be 2 pints / yd³.

3. DRYING

- 3.1 General: In order to promote the absorption of the surface applied corrosion inhibitor, it is necessary to remove the absorbed water in the concrete below the level of the reinforcing steel.
- 3.2 Expansion: Prior to beginning the drying operation, expansion joints must be cleaned and joint sealer removed. The joints must be monitored and the heating and/or drying rate must be reduced if complete closure of a joint becomes imminent. It shall be the responsibility of the contractor to reseal the expansion joints at the completion of the job.
- 3.3 Drying Method: Gas-fired, radiant infrared heaters shall be used to dry the concrete. The heaters shall be sufficient in number and size to cover the entire width of the deck for a distance of at least 4 ft, but no more than 20 ft, in the longitudinal direction for each heater setup. The heater units should be mounted on steel casters to permit easy movement from one set-up to the next. The heating capacity of the heaters shall be sufficient to provide the following schedule of surface temperatures:

Time (minutes)	Surface Temperature (°F)
start	ambient
15	350 ± 25
until dry	350 ± 25

The surface temperature shall be monitored under each heater unit with welded, pad-type, copper-constantan, parallel, grounded thermocouple probes (quick-disconnect type) having an inconel sheath of sufficient length to extend from the center of the heater to outside the heated area. A heat shield of galvanized sheet metal shall be erected around the perimeter of the heaters extending from the deck surface to the height of the heater (s). Glass wool insulation (R-19) shall be placed on the deck over a 24-inch wide perimeter area around the heater group for each heater set-up to reduce thermal gradients.

- 3.4 Condition--Concrete Dry: Drying is considered to be complete when the temperature at a depth of ½" below the mean depth of reinforcing steel reaches a temperature of 180°F as measured by unsheathed, copper-constantan thermocouples having teflon conductor insulation and glass braid overall insulation. The thermocouples are to have welded hot junctions and set in ¼" diameter holes drilled in the bottom of the deck. The holes shall be backfilled with a fast set epoxy-gel suitable for work on overhead surfaces. A minimum of three embedded thermocouples will be used for each heater set-up: one at the bridge centerline, and one in the center of each lane. The thermocouples shall remain in place after drying is completed, to monitor cool-down.
- 3.5 Cool-Down: Immediately upon attainment of the drying criterion, the heaters will be moved and the dried area will be covered with R-19 insulation (to minimize thermal cracking by preventing too rapid cool-down of the surface). Heating of the next adjacent area shall immediately follow the placement of the insulation. The insulation shall remain in place until the surface temperature has

dropped below 100°F. The contractor shall make provision for preventing wind from blowing the insulation off the deck.

- 3.6 Weather Protection: Dried areas shall be protected from precipitation, runoff, and other sources of moisture prior to the application of the corrosion inhibitor. Any dried areas subjected to moisture prior to treatment must be re-dried at the direction of the inspector. Dikes constructed of compacted asphaltic concrete cold mix sealed with asphalt emulsion and placed in the roadway upgrade from the bridge deck have been found to be effective in diverting runoff.
- 3.7 Drying Time: The approximate heating time at each heater set-up is expected to be 40 minutes according to the surface temperature schedule required under section 3.3. The drying of the entire area must be carried out as a continuous operation until completed.

4. APPLICATION OF SURFACE APPLIED CORROSION INHIBITOR

- 4.1 General: Application of the surface applied inhibitor involves spraying the dry concrete with a liquid corrosion inhibitor. The inhibitor is to soak into the base concrete prior to overlay.
- 4.2 Corrosion Inhibitor
 - 4.2.1 Corrosion inhibitor to be applied (see inserts)
 - 4.2.2 Supplier (see inserts)
 - 4.2.3 Solvent to be mixed with corrosion inhibitor to produce desired concentration (see inserts)
 - 4.2.4 Desired concentration (see inserts)
 - 4.2.5 Application Rate (see inserts) The inhibitor can be successfully applied with an Hudson type, industrial sprayer.
 - 4.2.6 A total of three applications of the inhibitor are to be applied. (see inserts for application times)
- 4.3 Safety in Handling and Storing the Inhibitor

See inserts.

- 4.4 Weather Protection: Provisions must be made to prevent precipitation runoff from contacting the surface of the deck during the inhibitor application.

5. SURFACE PREPARATION

- 5.1 General: Prior to overlay the deck surface must be lightly shotblasted or sandblasted to remove any residues left by the inhibitors. This must be done to ensure adequate bond between the substrate concrete and the overlay.
- 5.2 Shotblasting or Sand Blasting: The concrete surface of the deck to be treated shall be lightly blasted with shot or sand to remove any oily or greasy residues left by the inhibitor.
- 5.3 Cleanup: Following the completion of shot or sandblasting, the treated surface of the bridge deck shall be cleaned to remove particulate matter and fines.

6. OVERLAY PLACEMENT

- 6.1 General: The deck shall be overlaid with inhibitor modified concrete with the specified cover depth.
- 6.2 Materials
- 6.2.1 Concrete batch specifications suitable for deck overlays will be supplied by the contracting officer.
- 6.2.2 The corrosion inhibitor (see inserts) will be added as an admixture at the batch plant
- 6.2.3 Properties of overlay concrete: The inhibitor modified concrete shall have the following properties:
- (a) Air Content: $7 \frac{1}{2}\% \pm 1\%$
- (b) 28-day compressive strength: equal to or greater than _____ psi. (n.b.: insert appropriate value)

6.3 Placement: The overlay shall be placed following standard practice. A thick concrete grout containing the corrosion inhibitor shall be applied to the substrate immediately prior to overlay. The grout shall not be allowed to dry or set before the overlay is placed. The overlay shall be moist cured for a period of 3 days after placement. In addition to standard quality control procedures, bond strength tests shall be run in accordance with ACI 503R. Failure of a section of the overlay to meet minimum bond strength requirements shall result in the removal and replacement of that section.

**Insert Set I.
Cortec 2020 and 2000**

- 4.2.1 Cortec 2020 is a water based inhibitor to be used as a surface treatment or by injection.
- 4.2.2 The product can be obtained from:
- Cortec Corporation
St. Paul, MN 55107
(612)-224-5643
- 4.2.3 None.
- 4.2.4 Cortec 2020 is packaged at the desired application concentration by the manufacturer.
- 4.2.5 Each application of Cortec 2020 shall be spray applied at the rate of 225 ft² / gallon.
- 4.2.6 A total of three applications of the inhibitor are to be applied at 1, and 8 hours after the initial application.

4.3 Safety and Handling of the Inhibitor

- 4.3.1 General: The inhibitor must be stored, handled and applied in such a manner as to prevent fire, and injurious exposure to personnel associated with the job and to the public. A material data form covering the hazardous characteristics of the inhibitor appears in Exhibit 1. Unsafe handling practice will be sufficient cause to discontinue work until the hazardous procedures are corrected. The handling and use of the inhibitor shall in all cases comply with the requirements of applicable Federal, State, and local safety requirements and ordinances.

4.3.2 Inhibitor Storage: The inhibitor should be stored in original shipping containers. Containers should be kept tightly closed and kept away from heat, open flame, and spark sources.

4.3.3 Personnel Protection: Personnel working with the inhibitor shall be provided with and use safety glasses or goggles, NIOSH approved respirator, and Chemical resistant rubber or plastic gloves. The contractor shall provide a field eye wash and safety shower to be used in the event of an accidental splash of inhibitor on the workers. Additionally worker shall be required to thoroughly wash hands with soap and water prior to eating, smoking, drinking, or using the lavatory.

4.3.4 Accidental Spills of the Inhibitor: Accidental spills should be absorbed on sweeping compound or other absorbent material. The compound may be incinerated or disposed of in accordance to existing Federal, State and Local environmental regulations.

4.4 Weather Protection: See general notes.

6.2.2 Cortec 2000 will be added to the overlay concrete at the rate of 2 lb per cubic yard of concrete at the batch plant.

Insert Set II., DCI

- 4.2.1 DCI is a water based inhibitor containing 30% by weight calcium nitrite solids to be used as a surface treatment or concrete admixture.
- 4.2.2 The product and technical assistance can be obtained from:
- Neal Berke
Construction Products Division
W.R. Grace and Company
62 Whittemore Ave
Cambridge, MA 02140
(617) 876-1400 Extension 3155
- 4.2.3 Ordinary tap water is used for dilution of the product to the application concentration.
- 4.2.4 The inhibitor is to be applied at a concentration of 15% by weight calcium nitrite solids. This concentration may be obtained by mixing equal parts DCI and water.
- 4.2.5 Each application of the DCI solution shall be spray applied at the rate of 150 ft² / gallon. The inhibitor can be successfully applied with a Hudson type industrial sprayer.
- 4.2.6 A total of three applications of the inhibitor are to be applied at 1 and 8 hours after the initial application.

4.3 Safety and Handling of the Inhibitor

- 4.3.1 General: The inhibitor must be stored, handled, and applied in such a manner to prevent injurious exposure to personnel associated with the job and to the public. A material data form covering the hazardous characteristics of the inhibitor appears in Exhibit 2. The handling and use of the inhibitor shall

in all cases comply with the requirements of applicable Federal, State and Local safety requirements and ordinances.

4.3.2 Personnel Protection: Personnel working with the inhibitor shall be provided with and use safety glasses or goggles, and rubber or other impervious gloves. Additional appropriate clothing should be worn to minimize skin contact.

4.3.3 Accidental Spills of the Inhibitor: Spills should be absorbed with an inert, non-combustible media and removed for disposal in accordance with existing Federal, State, and Local environmental regulations. Spills should be prevented from entering drinking water supplies and streams.

4.4 Weather Protection: See general notes.

6.2.2 DCI will be added as an admixture to the overlay concrete at the rate of 6 gallons / cubic yard of concrete at the batch plant. DCI acts as a set accelerator and requires the following additional admixtures:

(a) Darasen 100 or other approved ASTM C 494 Type G high range water reducer to be added at the rate of 12 oz / 100 lbs cement.

(b) Daratard-17 or other approved ASTM C 494 Type B & D initial set retarder to be added at the rate of 6 oz / 100 lbs cement.

These addition rates are presented as guidelines. Trial batches should be constructed to ensure proper workability and set time.

Insert Set III., Alox 901

- 4.2.1 Alox 901 is an oxygenated hydrocarbon to be used as a surface treatment.
- 4.2.2 The product can be obtained from:
- Alox Corporation
3943 Buffalo Ave.
P.O. Box 517
Niagara Falls, NY 14302
(716) 282-1295
- 4.2.3 Denatured ethyl alcohol is used as a solvent to obtain the inhibitor solution.
- 4.2.4 The inhibitor is applied at a concentration of 4.7% by weight Alox 901 in denatured ethyl alcohol. The inhibitor must be field mixed at the job site.
- 4.2.5 Each application of Alox 901 shall be spray applied at the rate of 70 ft² / gallon. The inhibitor can be successfully applied with an industrial grade garden sprayer.
- 4.2.6 A total of four applications of the inhibitor are to be applied at 1, 2 and 4 hours after the initial application.

4.3 Safety and Handling of the Inhibitor

- 4.3.1 General: The inhibitor must be stored, handled and applied in such a manner as to prevent fire, explosion, and injurious exposure to personnel associated with the job and to the public. A material data form covering hazardous characteristics of the inhibitor appears in Exhibit 3. Unsafe handling practices will be sufficient cause to discontinue work until the hazardous procedures are corrected. The handling and use of the inhibitor shall in all cases comply with

the requirements of applicable Federal, State, and Local safety requirements and ordinances.

4.3.2 Storage of Inhibitor Materials: The Alox 901 and denatured ethyl alcohol shall be stored in original shipping containers prior to application. Maximum alcohol storage temperature shall not exceed 90°F (32°C). The storage facility shall be constructed in such a fashion as to provide protection from direct sunlight, fire hazard, and oxidizing chemicals. Sufficient ventilation shall be maintained in the storage facility to prevent the hazardous buildup of alcohol vapor concentrations in the storage air space. "Warning" and "No Smoking" signs shall be placed at appropriate intervals.

4.3.3 Fire Protection: Four 20-lb nontoxic, dry chemical fire extinguishers meeting Underwriters Laboratories, Inc. approval for Class A, B, and C fires, with a minimum rating of 20 A, 80 B, C shall be furnished by the contractor and kept near the alcohol storage area.

4.3.4 Personnel Protection: Personnel working with the inhibitor shall be provided with and use safety eyeglasses or goggles, and oil impervious gloves.

4.3.5 Accidental Spills of the Inhibitor: The inhibitor must be prevented from entering streams and waterways. Attempt to recover and recycle accidental spills, non-recyclable spills should be absorbed with vermiculite or dry sawdust, cleaned up with non-sparking tools, and disposed of by methods such as incineration complying with government regulations.

4.4 Mixing of Inhibitor and Denatured Alcohol: The Alox 901 shall be mixed with the denatured ethyl alcohol to the specified concentration prior to

application. Mixing shall be accomplished by using electric-motor-driven (explosion proof), propeller type stirrers.

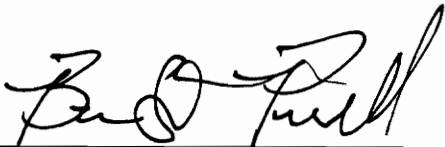
4.5 Weather Protection: See 4.4 in general notes.

6.2.2 No corrosion inhibitor of any type will be added to the overlay concrete unless specified by the engineer.

Vita

Brian Douglas Prowell was born February 12, 1967 in Shiremanstown, Pennsylvania. He graduated from Mechanicsburg Area Senior High in Mechanicsburg, Pennsylvania in June, 1985. In August of 1990 he received a Bachelor of Science in Civil Engineering from the Pennsylvania State University (after an initial start in mechanical engineering at George Washington University.)

He entered graduate school in the Transportation and Materials Division of the Department of Civil Engineering at Virginia Polytechnic Institute and State University in January, 1991. Mr. Prowell worked as a graduate research assistant at the Structures and Materials Laboratory while attending graduate school. A Master of Science in Civil Engineering is expected in August 1992.

A handwritten signature in cursive script, appearing to read "B. D. Prowell", is written over a horizontal line.

Brian Douglas Prowell