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Time-to-Corrosion of Reinforcing Steel in Concrete Slabs

Volume VI,
Calcium Nitrite
Admixture



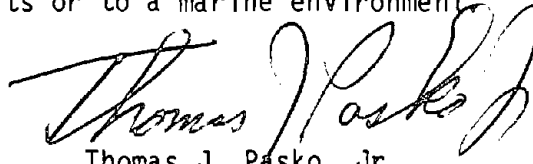
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FOREWORD

This report presents the finding of an outdoor long-term exposure study of reinforced concrete slabs containing admixed calcium nitrite as a corrosion inhibiting protective system. The tests were performed under conditions which simulated those found in typical highway bridge decks and the results are compared to those obtained on uncoated (black) steel. The concrete in the slabs contained variable amounts of chloride ions admixed during mixing to accelerate the initiation of the corrosion process. The report will be of interest to corrosion/bridge engineers and designers of reinforced concrete structures exposed to deicing salts or to a marine environment.



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Director, Office of Engineering
and Highway Operations
Research and Development

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16. Abstract <p>Eighteen relatively large reinforced concrete slabs were fabricated in 1980 using calcium nitrite admixture with black (uncoated) steel. Their performance is compared with uncoated steel in concrete without admixtures. The slabs were placed in two lifts: the bottom lift consisted of a bottom mat of reinforcing steel in chloride-free concrete, and a top lift consisting of the top mat rebars in concrete contaminated with various quantities of sodium chloride. All the electrical connections between the reinforcing mats were made exterior to the slabs so that the corrosion current flow could be measured.</p> <p>After curing, the slabs were mounted above ground and exposed to the environment of the Washington, D.C., Northern Virginia area. They were periodically subjected to additional chloride exposure while being monitored for the initial 1-year period.</p> <p>Findings of the study indicate that the calcium nitrite can be effective in reducing rate of corrosion for black reinforcing steel embedded in salt-contaminated concrete up to Cl⁻/No₂⁻ ratio of 0.9. The other volumes in this series are:</p> <table border="1"> <thead> <tr> <th>FHWA No.</th> <th>Vol. No.</th> <th>Short Title</th> </tr> </thead> <tbody> <tr> <td>RD-73/32</td> <td>I</td> <td>Effect of Mix Design and Construction Parameters</td> </tr> <tr> <td>RD-73/33</td> <td>II</td> <td>Electrical Potential Data</td> </tr> <tr> <td>RD-76/70</td> <td>III</td> <td>Performance after 830 Daily Salt Applications</td> </tr> <tr> <td>RD-82/02B</td> <td>IV</td> <td>Galvanized Reinforcing Steel</td> </tr> <tr> <td>RD-83/012</td> <td>V</td> <td>Calcium Nitrite Admixture or Epoxy Coated Reinforcing Bar</td> </tr> </tbody> </table>						FHWA No.	Vol. No.	Short Title	RD-73/32	I	Effect of Mix Design and Construction Parameters	RD-73/33	II	Electrical Potential Data	RD-76/70	III	Performance after 830 Daily Salt Applications	RD-82/02B	IV	Galvanized Reinforcing Steel	RD-83/012	V	Calcium Nitrite Admixture or Epoxy Coated Reinforcing Bar
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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
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LENGTH

in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

in ²	square inches	645.2	millimetres squared	mm ²
ft ²	square feet	0.0929	metres squared	m ²
yd ²	square yards	0.836	metres squared	m ²
mi ²	square miles	2.59	kilometres squared	km ²
ac	acres	0.395	hectares	ha

MASS (weight)

oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

VOLUME

fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft ³	cubic feet	0.0328	metres cubed	m ³
yd ³	cubic yards	0.0765	metres cubed	m ³

NOTE: Volumes greater than 1000 L shall be shown in m³.

TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C
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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
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LENGTH

mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

mm ²	millimetres squared	0.0016	square inches	in ²
m ²	metres squared	10.764	square feet	ft ²
km ²	kilometres squared	0.39	square miles	mi ²
ha	hectares (10 000 m ²)	2.53	acres	ac

MASS (weight)

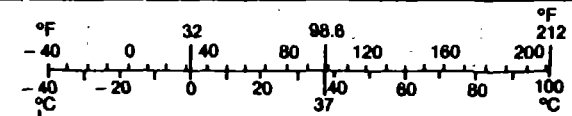
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m ³	metres cubed	35.315	cubic feet	ft ³
m ³	metres cubed	1.308	cubic yards	yd ³

TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F
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These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

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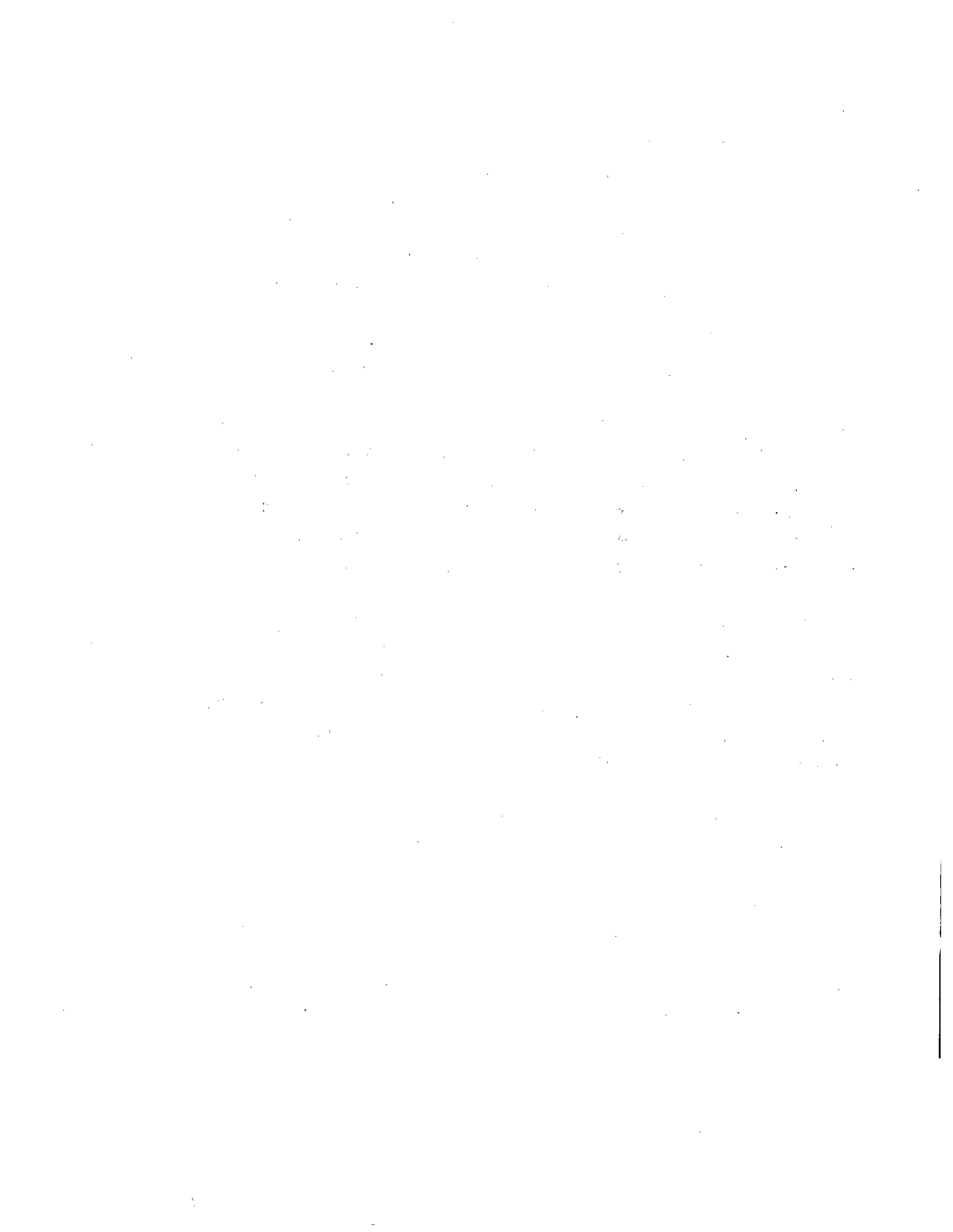
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INTRODUCTION AND BACKGROUND

Studying the effects of calcium nitrite and mix design on the long-term corrosion resistance of black steel in chloride-contaminated concrete has shown that the addition of calcium nitrite significantly improves the corrosion inhibition properties.⁽¹⁾ On the other hand, recent research has shown that the calcium nitrite as corrosion inhibiting admixture did not significantly delay the initiation of corrosion as compared to control concrete specimens.⁽²⁾ The severity of subsequent corrosion (total amp-hours of corrosion current) in black steel and strands, however, was significantly reduced compared to control concrete specimens. In another study, calcium nitrite was compared with calcium chloride as an accelerator for curing of the concrete mixtures.⁽³⁾ The study concluded that calcium nitrite significantly delayed the on-set of corrosion of black steel reinforcement and subsequent concrete cracking. A Louisiana Department of Transportation study concluded that calcium nitrite as a corrosion inhibiting admixture is beneficial in protecting the black steel reinforcing against corrosion in salt-contaminated concrete.⁽⁴⁾

In 1980, the Federal Highway Administration (FHWA) initiated an outdoor research study using calcium nitrite as an admixture in salty concrete to inhibit the corrosion of black steel reinforcing rebars.⁽⁵⁾ In a comparison series of test slabs, epoxy-coated rebars were used as another alternative corrosion protection system. The long-term results on that system will be reported separately at another time.

This report presents the long-term results from use of a calcium nitrite admixture to inhibit the corrosion of black steel reinforcing bars in chloride contaminated concrete. This research was motivated by the need for an alternative corrosion protection system to mitigate the severe corrosion of black reinforcing steel bars in marine and deicing salt environments.

The life of bridge decks and substructure are significantly reduced by the corrosion of unprotected (black) steel. Inhibition of corrosion can be

achieved after the mechanism of corrosion and the factors affecting it are understood. Recent research has helped to explain the corrosion phenomenon for black steel rebars in salt-contaminated concrete when oxygen and water are present in optimum quantities.(6)

It is generally accepted that the principal cause of corrosion is the occurrence of macroscopic corrosion cells between the top and bottom mats of rebars (those in which large quantities of steel drive corrosion at the anodic steel). Microscopic cells which occur locally (those which operate on a small section of the same reinforcing rebar) are less important. The corrosion cells are developed due to the presence of chloride ions in the concrete, which produce an electrical potential difference at the top mat (chloride-contaminated concrete) and between the top and bottom mat (chloride free concrete). This electrical potential difference at the top mat and between the two mats produces the flow of an electrical (corrosion) current. The amount of iron consumed in forming the various corrosion products is directly related to this measured corrosion current. The corrosion rate is controlled by the ability of the cathodic bottom mat to reduce oxygen while the anodic top mat is subject to iron loss.

DESCRIPTION OF SPECIMENS

A total of 18 slabs were used in this test series. Five slabs with no calcium nitrite were control specimens; designated as numbers 211 through 215. The rest were test specimens designated as slabs numbers 216 through 228 and had 2.75 percent of calcium nitrite by weight of cement in both the top and bottom lifts of concrete. Nominal chloride contents of 0, 5, 10, 15, 20, 25 and 35 pounds Cl^-/yd^3 were mixed in the top lift concrete of the calcium nitrite slabs while the control slabs were fabricated with 0, 5, 15 and 35 pounds Cl^-/yd^3 . The research design posed a severe corrosion environment since the chloride was added directly to the fresh concrete, thus, complicating the reaction mechanism for normal passivation of the steel by concrete and the nitrite ions. In addition, the concrete quality (water-cement ratio of 0.53) was quite poor.

Each slab was 2 ft by 5 ft by 6 in thick and cast in two lifts. The lower lift was 3.5 in thick and cast with chloride free concrete. The 2.5-in thick top lift contained varying amounts of admixed chloride ions and was cast 1 to 3 days after the lower lift. The upper lift was reinforced by a mat of rebars, consisting of four Number 5 longitudinal bars 51 in long and two Number 4 cross bars 18 in long. The lower mat consisted of seven Number 5 longitudinal bars, 51 in long, and three Number 4 cross bars 18 in long. The slab design is shown in figure 1. All rebars met AASHTO specifications M-31. The clear concrete cover over the top mat was 3/4 in and 1 in concrete cover below the bottom mat, leaving a clear 2 in of concrete between the two mats.

The concrete in each slab had a mixing ratio of 1:1.76:2.36 for cement, fine and coarse aggregates, by weight. Detailed properties of the concrete mix design are shown in table 1. The fine aggregate was white marsh sand which has a specific gravity of 2.64 and a fineness modulus of 2.6. The coarse aggregate was riverton limestone which has a specific gravity of 2.77 and 3/4-in maximum size, graded to the midpoint of the AASHTO M-43 size number 67 specification. All coarse aggregates were separated into four sizes which were then batched separately to ensure gradation control. The concrete was mixed in 9-ft³ batches in an 11-ft³ rotary drum mixer and placed in two lifts. The lower lift was cured with wet burlap and then wire brushed prior to the placement of the top lift, 1 to 3 days later. The top lift was also cured with wet burlap and polyethylene for 14 days. The slabs were mounted on 3-ft posts at the FHWA outdoor exposure site.

INSTRUMENTATION

No. 12 gauge stranded copper lead wires with teflon insulation were used to connect the rebar mats to the switch box. The bars were attached as follows. First, the ends of the bars were sand blasted, a 1-in-wide area on one side of the bar was flattened, and a 1/4-in-diameter hole was drilled through the bar to receive a 1/4-in bolt for fastening the lead wire to it. The attachment area was then well coated with epoxy. Electric leads were attached to all top mat rebars and to two of the bottom mat rebars before the concrete was cast.

All lead wires were extended outside the concrete to facilitate the corrosion measurement. The switch was kept at the on-position to maintain the electric coupling at all times except when gathering data. Nine thermo-couples were embedded in each slab for temperature monitoring. Figure 2 shows the front and rear view of the instrumentation interface box attached to the wired slab.

TESTING PROCEDURES

After the slabs were cast and cured, the upper surface of all slabs (except numbers 212 and 217) were ponded with a 3 percent sodium chloride solution until the corrosion current developed in a control slab which was initially chloride free. This ponding period was 46 days. After that time, the ponding was discontinued and the slabs exposed to natural Washington D.C., Northern Virginia area climatic conditions. Usually data was gathered twice a month in the beginning, and later on, once a month. Data collection was usually completed within a 1-week period. Measurements were halted in case of rain and resumed when the excess water on the slab evaporated and the surface appeared dry. At the instrumentation box attached to the front of the slabs, the following data was collected with the coupling switch at on-position (bottom and top mat connected) in the following sequence:

- (a) Thermo-couple readings for monitoring the temperature.
- (b) The voltage drop across a standard 0.5 ohm precision resistor. This measured voltage was then converted to actual amount of current flow between the bottom and top mats.

The next set of slab readings were made with the switch at the off-position:

- (c) The potential difference between the top and bottom rebar mats to measure the driving voltage of the corrosion cell (measured instantly after the switch is turned off).

- (d) The electrical potential between the top mat and a copper/copper sulfate (CSE) reference half-cell measured on the top concrete slab surface at three marked positions.
- (e) Same as (d) except that CSE reference half cell is placed at bottom of concrete slab surface for measuring bottom mat electrical potential.
- (f) The electrical resistance between top and bottom mats using a 1000 Hz AC meter.

The corrosion current measurement (b) was completed first (switch 'on') since uncoupling (switch 'off') causes rapid depolarization of corrosion cells, yielding inaccurate current flow readings. Once depolarization occurs, it takes a while to restore a steady - state polarization condition. Measurements (c) were taken instantly after uncoupling followed by measurements (d) and (e).

DISCUSSION AND INTERPRETATION

The appendix contains the details for calculation and presentation of the measured data over a 7-year testing period for one typical reinforced concrete slab. For each tested slab, there are three typical tables 8, 9, and 10 and four figures 5, 6, 7 and 8 for visual inspection of the data.

CORROSION CURRENTS

Table 2 summarizes the corrosion data for the 18 instrumented slabs under test. Details on the properties of concrete for individual slabs and fabrication details are given elsewhere.⁽⁵⁾ Table 3 contains the average weighted 70 °F corrosion currents for four control slabs (211, 213, 214 and 215 without calcium nitrite) and the average measured chloride content at the top rebar mat level. Besides this the table has additional data from two other control slabs (designated as 202 and 234) which had been fabricated for an epoxy coated rebar study. They had black steel top and bottom mats; no

calcium nitrite and contained 15.6 lbs Cl⁻/yd³ of concrete. Figure 3 shows a plot of this data with a least square fit line. The least-square fit line gave this equation:

$$\text{Corrosion current (in } \mu\text{A)} = 277 (\text{Cl}^- \text{ content in lbs/yd}^3 - 1.44)$$

Also shown in figure 3 are the true weighted average corrosion current data for the calcium nitrite slabs versus average chloride content at top rebar mat. Table 4 includes the derived corrosion currents from least square fit line in figure 3 for the slabs without calcium nitrite and compares it with the measured corrosion current data for slabs with calcium nitrite and known chloride content. The weighted average corrosion currents listed in tables 2, 3, and 4 were calculated by the following equation:

$$\text{Weighted average corrosion current (in } \mu\text{A)} = \frac{\text{total cumulative amp. hr}}{\text{total days} \times \frac{24 \text{ hr}}{1 \text{ day}}} \times \frac{10^6 \mu\text{A}}{1 \text{ amp}}$$

Previous research on black steel rebars without calcium nitrite has shown that a strong macroscopic corrosion cell will develop between the top mat of reinforcing steel in chloride contaminated concrete and the bottom mat of steel in chloride-free concrete. The data in table 4 and figure 3 show that black steel reinforced concrete slabs containing up to 2.75 percent calcium nitrite at top mat has developed a varying strength macroscopic corrosion cell between the top and bottom mats, depending upon the amount of chloride ions at the top mat rebar level. Qualitatively, it appears that the rate of corrosion (as measured by the corrosion current value) increases as the ratio of chloride to nitrite increases. This trend is observed for slabs 216 through 228 with some exceptions. The anomalous results on a few slabs may be due to the debonding of bottom and top concrete lift and excessive corrosion associated concrete cracking at the top slab surface. On reviewing the corrosion current data in table 4, it appears that for chloride to nitrite ratios ranging between 0.29 to 1.11, reductions in the corrosion rate by an approximate factor of 10 is achieved. In other words, it would require 10 years to consume the same amount of iron as is consumed in 1 year by reinforced concrete slabs without calcium nitrite. Moreover, table 4 shows

that chloride to nitrite ratio above 1.11 provides a reduction in corrosion rate by a factor of 2 only. Therefore, for calcium nitrite to be effective as corrosion inhibitor (based on corrosion current data only), the ratio of chloride to nitrite should be close to 1.1 or less. The use of calcium nitrite as a corrosion inhibitor for a Cl^-/NO_2^- ratio greater than 1 does not appear to be significantly beneficial.

HALF CELL POTENTIALS

Table 5 contains the summary of the data on half cell potentials (measured with reference to CSE half cell) for the top and bottom reinforcing mat. The last column in table 5 lists the average potential differences between the two mats. In general, slabs 216 to 221 with Cl^-/NO_2^- ratio less than 1, have smaller potential differences between the two mats and ranges from a low of a few mv to a high of 35 mv. In contrast, slabs 211, 213, and 214 containing no calcium nitrite but having similar amounts of chloride to slabs 216 to 221 have larger average potential differences between the top and bottom mats, indicating more corrosion. Slabs 224 to 228 with a Cl^-/NO_2^- ratio greater than 1.1, have potential differences in the range of -52mv to -149 mv. These higher potential differences values are indicative of larger corrosion macro-cell compared to the slabs with a Cl^-/NO_2^- ratio less than 1. The potential difference values between the two reinforcing mats is approximately proportional to the strength of galvanic cells formed due to differential chloride concentration in two lifts and is somewhat analogous to the driving voltage values reported in table 2. It is incorrect to interpret the absolute measured half cell potential values for the top mat (embedded in chloride contaminated concrete) and the bottom mat (embedded in salt free concrete) according to ASTM C 876-80 standard, since both the mats are polarized (coupled) until the measurement time. The half cell potential values for corrosion, uncertain condition, and no corrosion as quoted in the ASTM C 876-80 standard can not be fully correlated with the measured values in table 5. However, it is quite apparent from the half cell potential difference data

between the two mats that calcium nitrite is an effective corrosion inhibitor for a Cl^-/NO_2 ratio of 1 or less in the hardened concrete.

RESISTIVITY MEASUREMENTS

A review of the data in table 6 reveals a wide scatter of average concrete resistivity values for the period 1980 to 1986 among different slabs with no significant differences between the slabs containing calcium nitrite and the control slabs. It is also apparent that neither calcium nitrite nor chloride contents have significant influence on the resistivity values. For most of the slabs, there is an increase in resistivity values for the year 1986 as compared with the 1980 values. This increase in resistivity values with the passage of time may be due to: (1) drying up of interior concrete (since the measured resistance is for the interior concrete); (2) accumulation of corrosion by-products in a few slabs with high chloride content; and (3) partial debonding between the two lifts due to construction deficiencies at the time of slab fabrication or thereafter. For slabs 212 and 228, there was a marked increase in the resistivity, up to 10 fold; indicating that these two slabs have been debonded. This debonding affects most of the nondestructive measurements such as driving voltage, corrosion current, and average potential differences between the top and bottom mats.

VISUAL SURVEY

The condition of the slabs photographed in June 87 is shown in figure 4 and a summary of the visual survey data is presented in table 7. From the table, it is apparent that the slabs containing chloride in the range of 6.9 to 23.3 lbs Cl^-/yd^3 but no calcium nitrite have developed significant cracking (slabs 213, 214, 215, 202 and 234) and the rust products are leaching out of those cracks.

On the other hand, the slabs with varying chloride levels and containing fixed levels of calcium nitrite (up to a Cl^-/NO_2 ratio of 0.90) did not show any visible cracking or rust spots on the concrete surface (slabs 216 to 221 except slab 218). These slabs had chloride concentrations up to 11.7 lbs Cl^-/yd^3

of concrete. Slab 222, which contained 13.4 lbs Cl^-/yd^3 ($\text{Cl}^-/\text{NO}_2^- = 1.06$), had a few fine cracks and two rust spots. Similarly slab 223 containing $\text{Cl}^-/\text{NO}_2^-$ ratio of 1.13 has a moderate number of cracks and the rust is coming out of these cracks. For slabs 224 to 228 with a $\text{Cl}^-/\text{NO}_2^-$ ratio of 1.30 to 1.79, there are a large number of wide cracks and major rusting.

It is quite apparent that calcium nitrite is passive toward black reinforcing steel up to a $\text{Cl}^-/\text{NO}_2^-$ ratio of 0.90. The passive film breaks down when this ratio exceeds 0.90.

CONCLUSIONS

The testing of 18 reinforced concrete slabs for 7 years to determine the effectiveness of calcium nitrite as a corrosion inhibiting admixture has led to the following conclusions. These conclusions are based on the periodic non-destructive measurements for corrosion current, half cell potential, driving voltage, and resistivity in addition to a visual survey at the end of the 7 years.

1. In general, the nondestructive corrosion measurement techniques and the collected data correlate well with the visual survey of the concrete slabs under test. The nondestructive techniques described earlier and in this report offer a useful approach in monitoring the effectiveness of various corrosion inhibiting admixtures and other additives when chloride contaminated concrete may not show any visible distress or rust on the surface at an early age. (5)
2. The magnitude of corrosion current flow between the mats in salt contaminated concrete and salt-free concrete, measured periodically, can be used semiquantitatively to monitor the performance of corrosion protection materials. Other measured parameters such as driving voltage, half-cell potential, and concrete resistivity are additional useful data for proper interpretation of the corrosion current flow data.

3. The use of calcium nitrite was effective in reducing the rate of corrosion for black reinforcing steel embedded in poor quality salt contaminated concrete up to a $Cl^-/\overline{NO_2}$ ratio of 0.9. This conclusion is based on both periodic nondestructive data collected over 7 years and a visual survey of the slabs. Although the slabs fabricated with a higher $Cl^-/\overline{NO_2}$ ratio (up to 1.11) indicated that there is a reduction in corrosion current flow by a factor of 10, the visual survey showed some cracking and rust spots on the concrete surface. The slabs with a $Cl^-/\overline{NO_2}$ ratio from 1.3 to 1.8 showed an average reduction in the corrosion current by a factor of 2.7, but did have cracks and major rusting out of cracks as well as on the surrounding concrete surface. In addition, there are some hollow and spalled areas present on these slabs (224 to 228).

4. Calcium nitrite appears to be effective because it does not allow a large electrical potential difference to develop between adjoining steel in the top mat or between top and bottom mats. In the absence of calcium nitrite, there would be cathodic and anodic areas which would allow the generation of corrosion current and dissolution of iron from the top mat in chloride contaminated concrete.

RECOMMENDATION

Calcium nitrite, if chosen as the corrosion protection system, should be added in sufficient quantities to the fresh concrete to provide a $Cl^-/\overline{NO_2}$ ratio of less than 1 at the steel level closest to the exposed concrete surface during the expected design life of the structure. The above chloride level is the expected accumulative value attained at the steel level due to the exposure of the concrete surface to deicer application or marine exposure. This recommendation is based on the results from the limited number of slabs tested in this study where most of the chloride ions were added along with nitrite ions at the time of construction. Here both the ions were engaged simultaneously in complicated competing reactions; corrosion versus passivation at the reinforcing steel surface. It is reasonable to assume that, for a normal

situation when chloride ions are penetrating more slowly into hardened concrete, Cl^-/NO_2^- ratios higher than 1.0 might be tolerable without undue corrosion.

There is a need for a detailed research study to determine the long-term stability and availability of sufficient nitrite ions since they are required only when the chloride ions have penetrated through the hardened concrete surface and started corroding the reinforcing steel. Studies have indicated that this period for accumulation of sufficient chloride ions (above threshold level for corrosion initiation) through 2 in of good quality concrete cover may be 7 to 12 years. On the other hand, poor quality concrete can accumulate adequate chloride ($1.25 \text{ lbs } Cl^-/\text{yd}^3$) at 1 in depth through 7 deicing salt applications. (8)

APPENDIX
METHOD OF ANALYSIS

Table 8: Corrosion Current and Iron Consumed

- 1st column: Represents the number of days the slab has been coupled
- 2nd column: Represents the measured driving voltage
- 3rd column: Represents the actual current between top and bottom mats for that particular day
- 4th column: Represents the current in column three adjusted to 70 °F temperature according to the following equation:

$$i_1 = \frac{i_2}{e^{2883 \left(\frac{1}{T_1} - \frac{1}{T_2} \right)}}$$

where:

i_1 = corrosion current calculated at temperature T_1 (70 °F)

i_2 = corrosion current measured at temperature T_2 (Field)

T_1 = temperature (in degrees Kelvin) at which one desires to know the corrosion current or resistance (70 °F)

T_2 = average temperature of the concrete (in degrees Kelvin)

e = natural base of logarithm

5th column: Represents the electrical resistance between top and bottom mats provided by the concrete and adjusted to 70 °F temperature according to the following formula:

$$R_1 = R_2 e^{2883 \left(\frac{1}{T_1} - \frac{1}{T_2} \right)}$$

where:

R_1 = resistance calculated at temperature T_1 (70 °F)

R_2 = resistance measured at temperature T_2 (Field)

6th column: Represents the average temperature of the slab

7th column: Represents the cumulative current in amp-hours since the coupling of the slab up to the date of the reading. For example, consider table for slab # 219-419, the cumulative amp-hours current at 576 days coupled was calculated as follows:

$$285.0 \text{ (adj. cur. to } 70 \text{ }^\circ\text{F)} + 96 \text{ (adj. cur. to } 70 \text{ }^\circ) \mu\text{A}$$

$$\frac{\quad}{2}$$

$$\times (576-554) \text{ days} \times \frac{24 \text{ hr.}}{\text{day}} \times \frac{1 \text{ Amp.}}{10^6 \mu\text{A}} = 0.10 \text{ Amp-hours}$$

$$0.10 + 3.51 \text{ (cumul. amp-hours @ 554 days coupled)} = 3.61 \text{ Amp-hours}$$

8th column: Represents the theoretical amount of iron consumed due to corrosion current adjusted to 70 °F. These values are obtained by multiplying the cumulative amp-hours in column seven by a factor of 1.04 gms/amp-hour.

$$\begin{aligned} \text{e.g. iron consumed for 576 days coupled} &= 3.61 \text{ amp-hours} \times \frac{1.04 \text{ gms}}{\text{amp-hours}} \\ &= 3.75 \text{ gms.} \end{aligned}$$

Table 9: Electrical Potentials

1st column: Represents number of days the slab has been coupled

2nd column: Represents the potential of embedded rate of corrosion probe in millivolts (none was installed in slab 219-419)

3rd column: Represents the top mat potential reading in millivolts at location 1

4th column: Represents the top mat potential reading in millivolts at location 2

5th column: Represents the top mat potential reading in millivolts at location 3

$$\frac{\quad}{3}$$

2

1

Slab plan view (locations of potential reading)

6th column: Represents the arithmetic average for the three top mat potential

Columns 7 through 9: The bottom mat potential readings at locations 1, 2, and 3 respectively at the bottom concrete surface of the slab

10th column: Represents the arithmetic average of the three bottom mat potential readings

11th column: Represents the difference between top and bottom mat potential and is obtained by subtracting the value of the bottom mat average potential from the top mat average potential

TABLE 10: Resistance and Resistivity

1st column: Represents the measurement date

2nd column: Represents the number of days the slab has been coupled

3rd column: Represents the mat-to-mat resistance measured and later adjusted to 70 °F (as explained earlier for 5th column in table 8)

4th column: Represents the percent change in mat-to-mat resistance since the initial reading. It is calculated as follows:

$$\text{Change in mat-to-mat percent} = \frac{\text{mat-mat } R \text{ } 70 \text{ } ^\circ\text{F} - \text{initial } R \text{ } 70 \text{ } ^\circ\text{F}}{\text{initial } R \text{ } 70 \text{ } ^\circ\text{F}} \times 100$$

Resistivity constant: Experimentally determined cell constant for the total reinforcing steel in the slab design.

Resistivity: Mat-to-mat $R \text{ } 70 \text{ } ^\circ\text{F}$ x cell constant; ohms-cm

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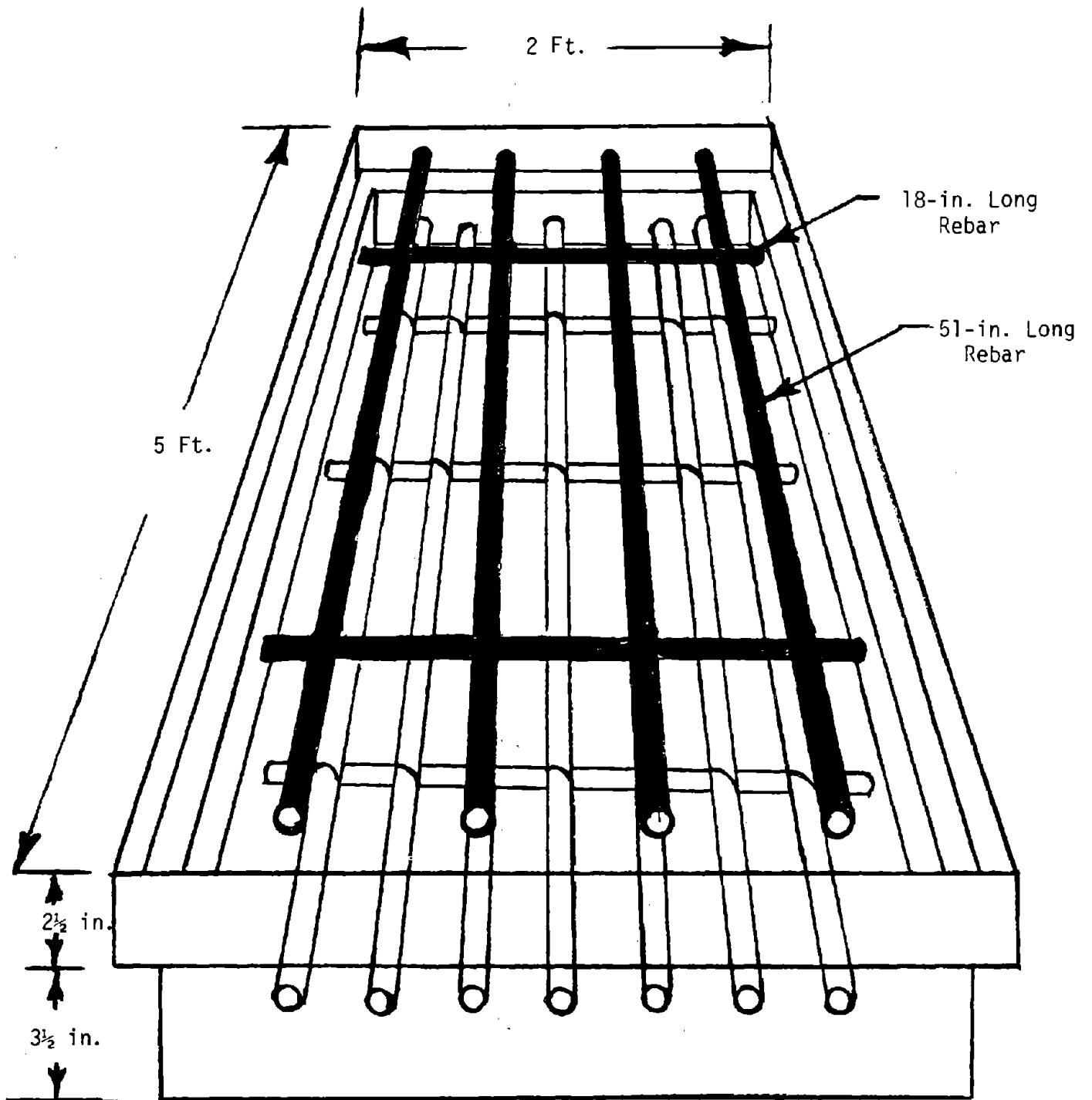
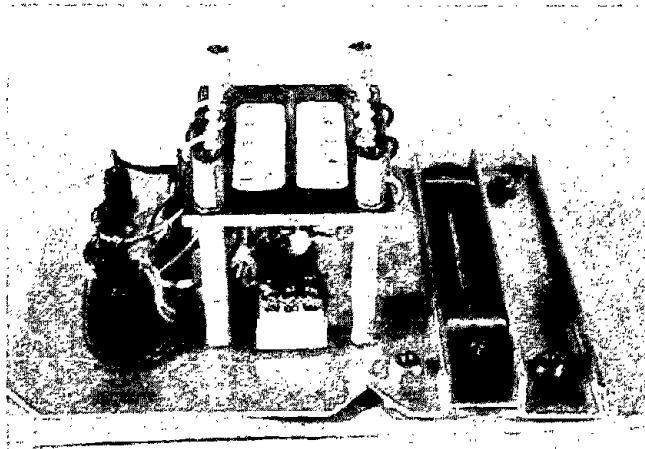
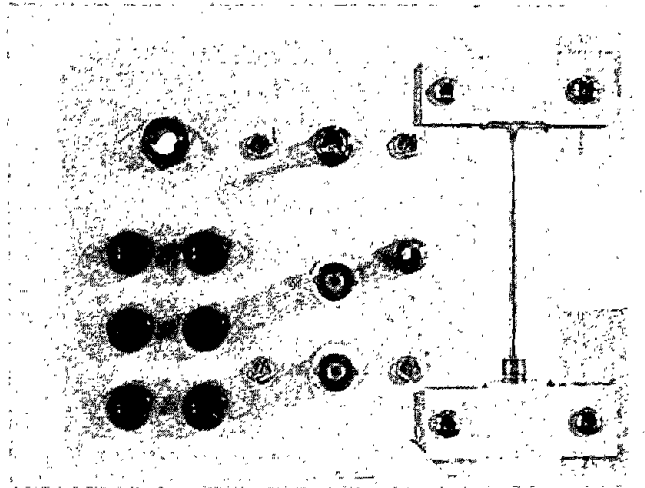


Figure 1. Standard slab design.

Rear



Front



Front After Wiring

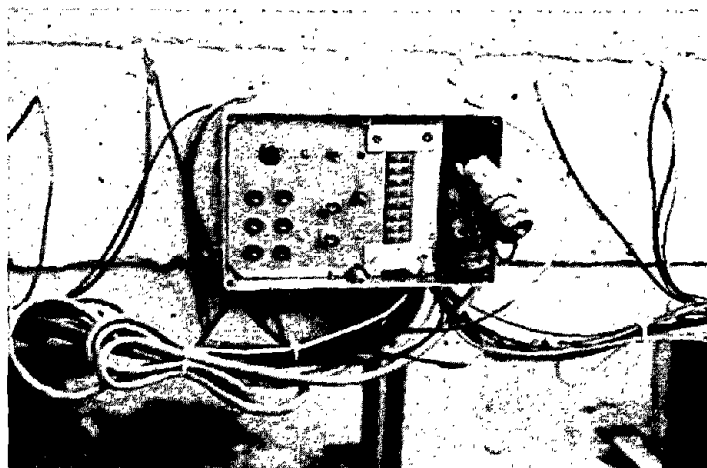


Figure 2. Instrumentation interface box.

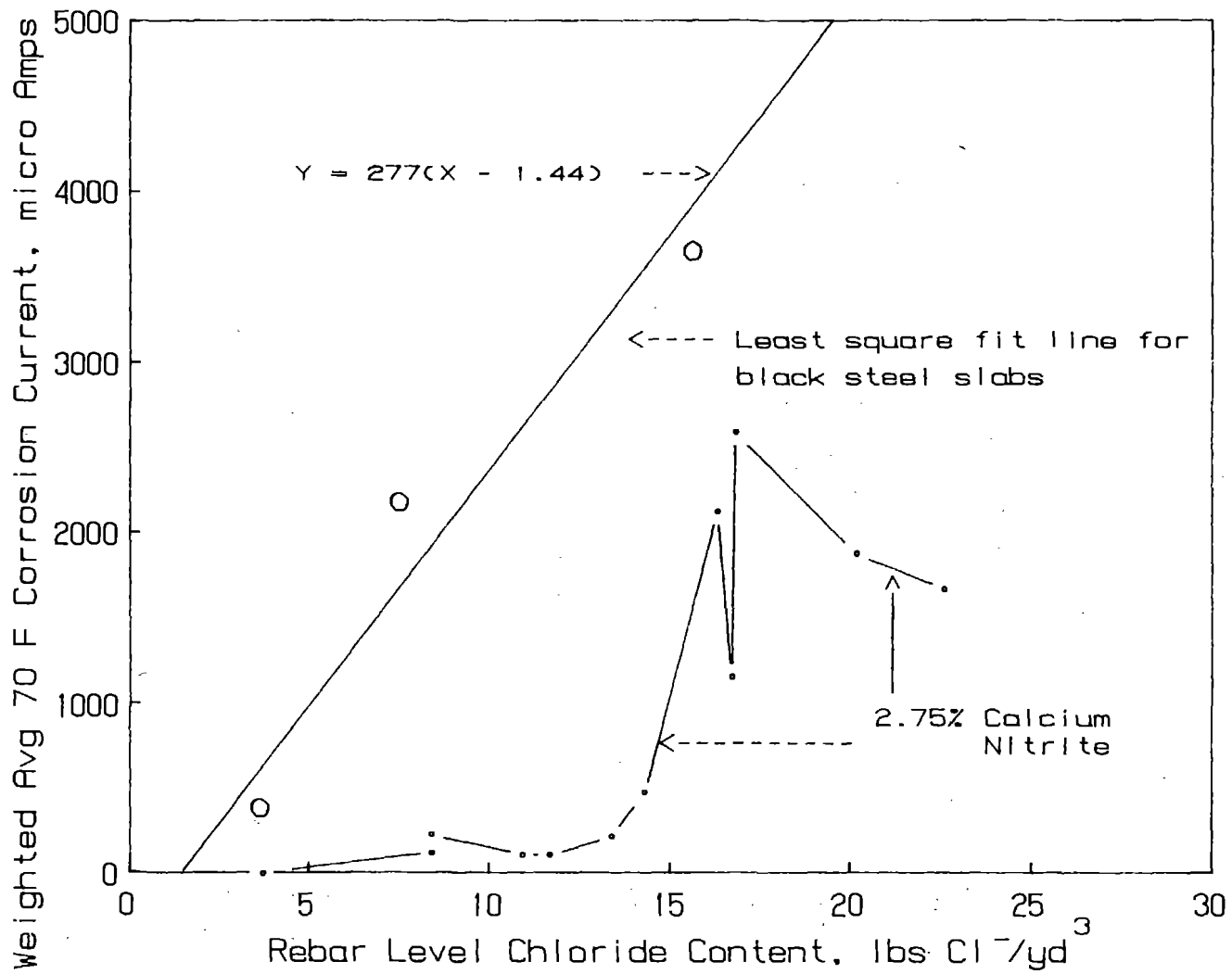


Figure 3. Corrosion current vs chloride in concrete slabs at reinforcing steel level.

Slab 211: No Calcium Nitrite;
3.6 lbs Cl⁻/yd³.

Slab 212: No Calcium Nitrite;
no Chloride.

Slab 213: No Calcium Nitrite;
7.9 lbs Cl⁻/yd³.



Figure 4. Condition of slabs 211 thru 228 @ 2429 days coupled (June, 1987).



Slab 214: No Calcium Nitrite:
6.9 lbs Cl⁻/yd³.

Slab 215: No Calcium Nitrite;
23.3 lbs Cl⁻/yd³.

Slab 216: 2.75% Calcium Nitrite;
3.7 lbs Cl⁻/yd³.

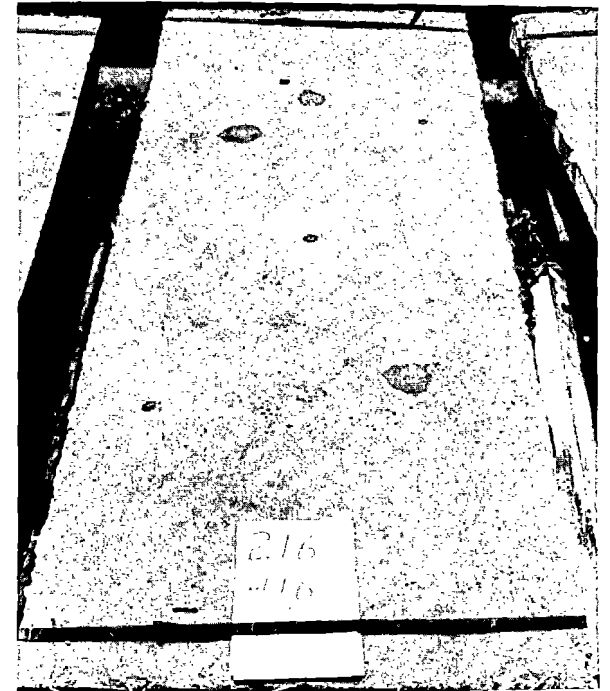


Figure 4. Condition of slabs 211 thru 228 @ 2429 days coupled (June, 1987). (Continued)

Slab 217: 2.75% Calcium Nitrite:
no Chloride.

Slab 218: 2.75% Calcium Nitrite:
8.4 lbs Cl⁻/yd³.

Slab 219: 2.75% Calcium Nitrite:
8.4 lbs Cl⁻/yd³.

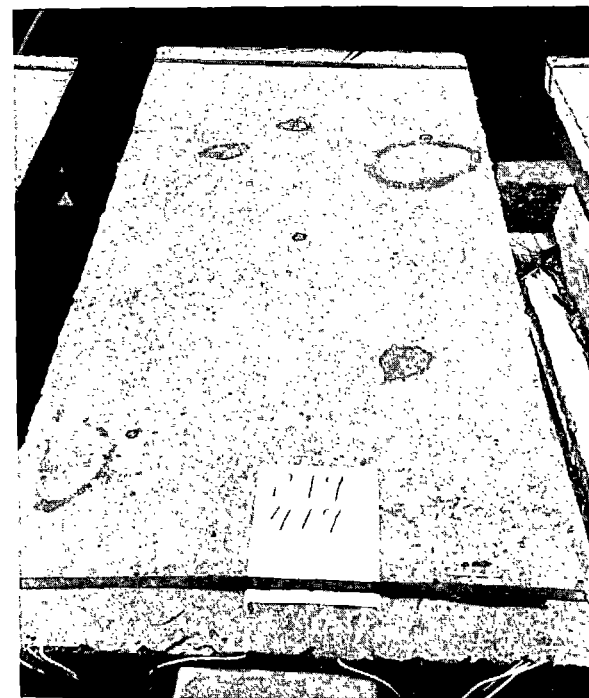


Figure 4. Condition of slabs 211 thru 228 @ 2429 days coupled (June, 1987). (Continued)

Slab 220: 2.75% Calcium Nitrite:
11.7 lbs Cl⁻/yd³.

Slab 221: 2.75% Calcium Nitrite:
10.9 lbs Cl⁻/yd³.

Slab 222: 2.75% Calcium Nitrite:
13.4 lbs Cl⁻/yd³.

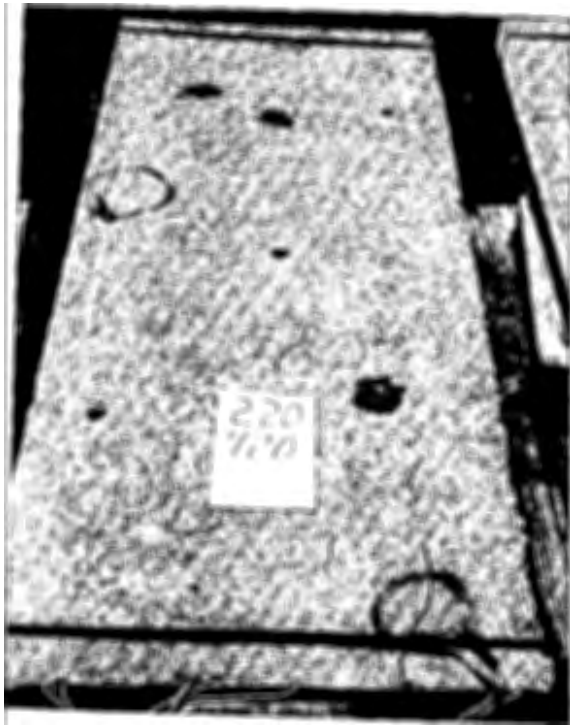


Figure 4. Condition of slabs 211 thru 228 @ 2429 days coupled (June, 1987). (Continued)

Slab 223: 2.75% Calcium Nitrite:
14.3 lbs Cl⁻/yd³.

Slab 224: 2.75% Calcium Nitrite:
16.7 lbs Cl⁻/yd³.

Slab 225: 2.75% Calcium Nitrite:
16.3 lbs Cl⁻/yd³.

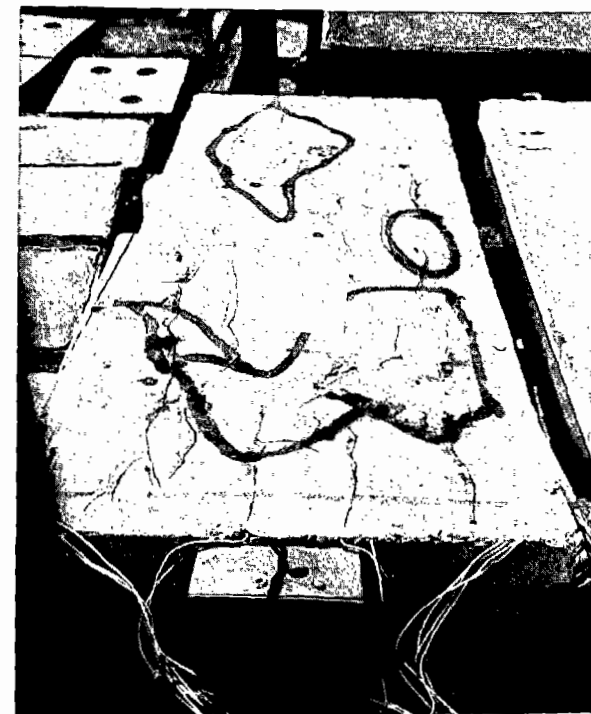
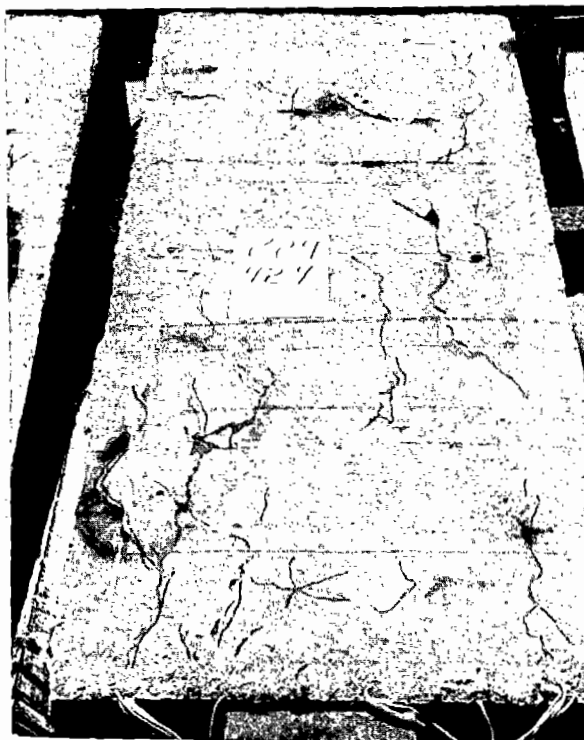
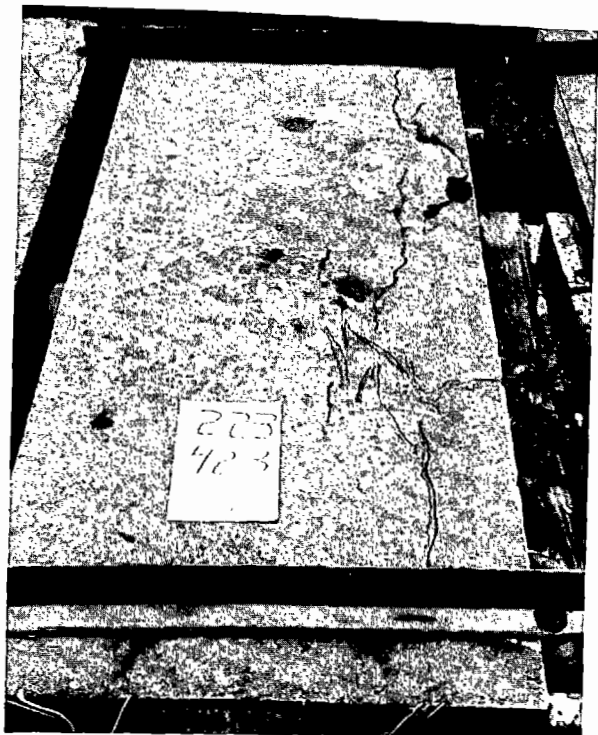


Figure 4. Condition of slabs 211 thru 228 @ 2429 days coupled (June, 1987). (Continued)

Slab 226: 2.75% Calcium Nitrite;
16.8 lbs Cl⁻/yd³.

Slab 227: 2.75% Calcium Nitrite;
20.2 lbs Cl⁻/yd³.

Slab 228: 2.75% Calcium Nitrite;
22.6 lbs Cl⁻/yd³.

24

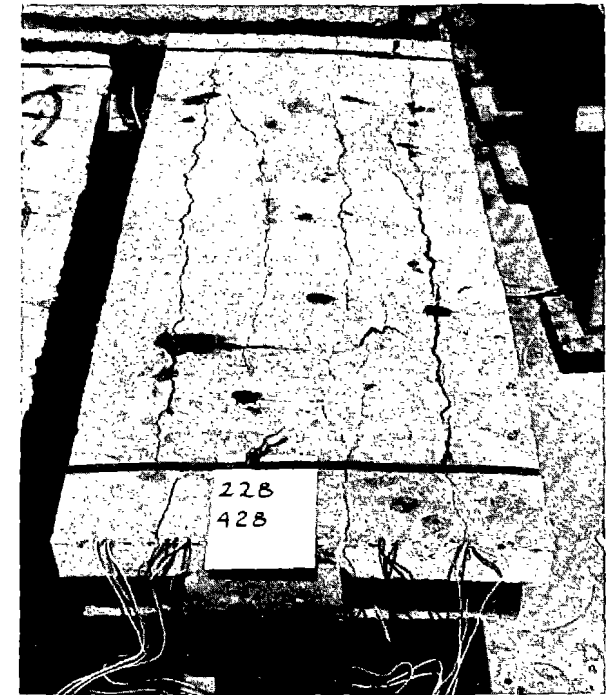
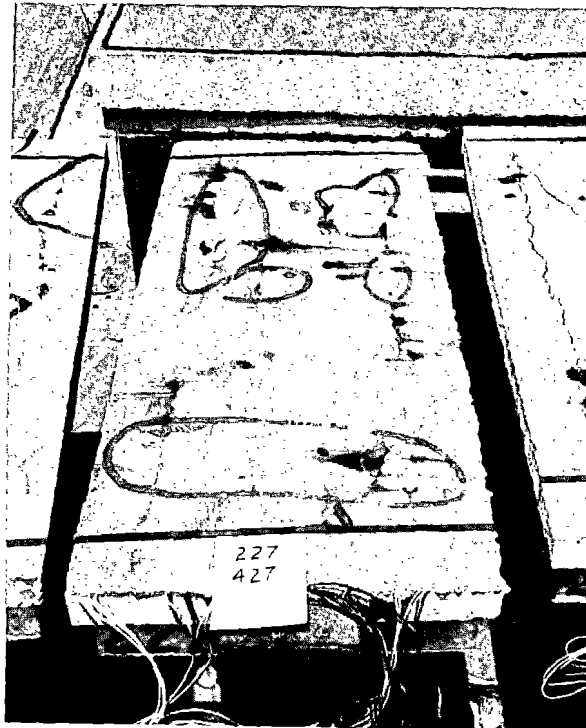


Figure 4. Condition of slabs 211 thru 228 @ 2429 days coupled (June, 1987). (Continued)

ADJUSTED CURRENT VS. DAYS COUPLED
ADJUSTED RESISTANCE VS. DAYS COUPLED
 SLAB NO. 219-419

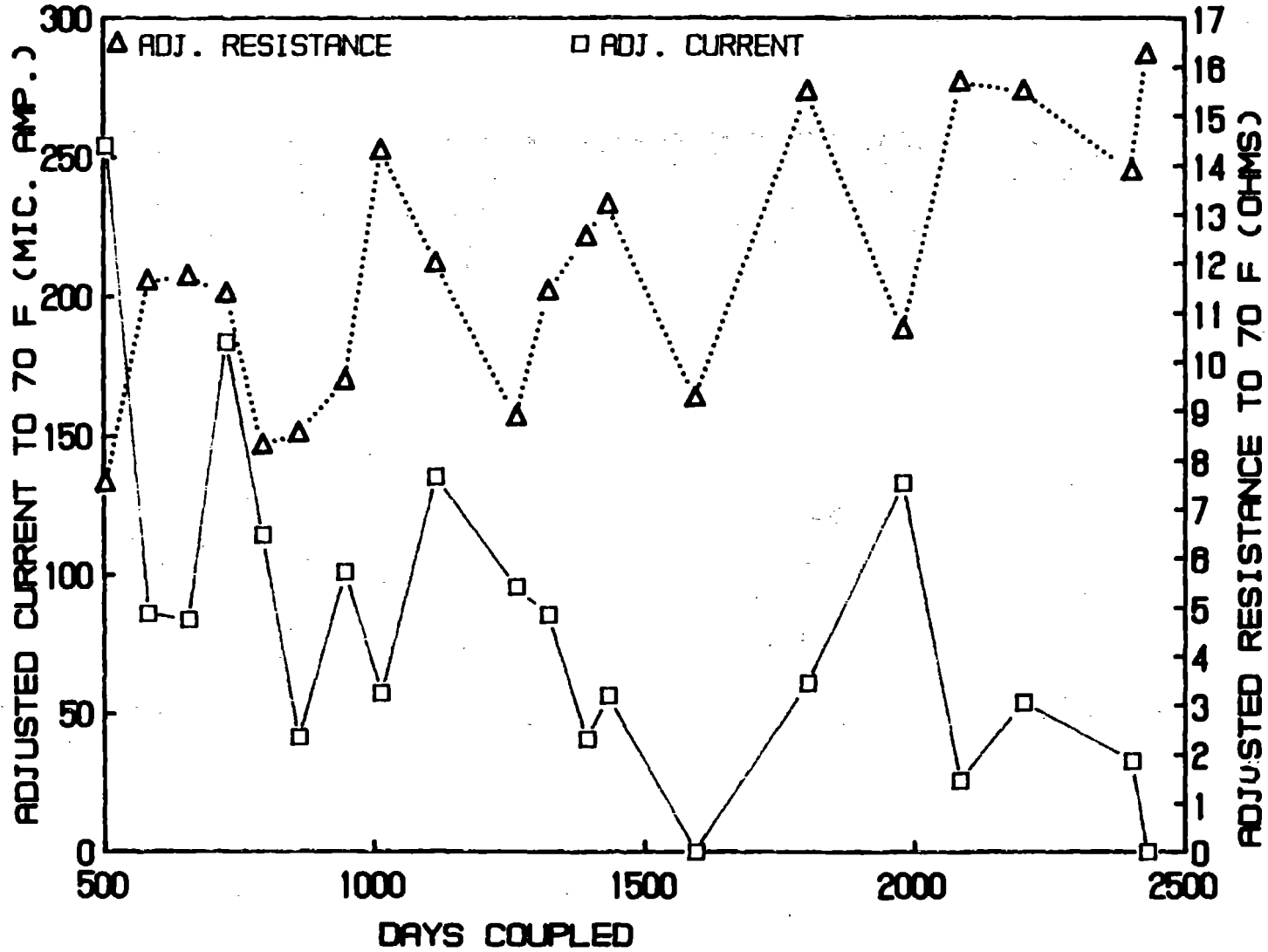
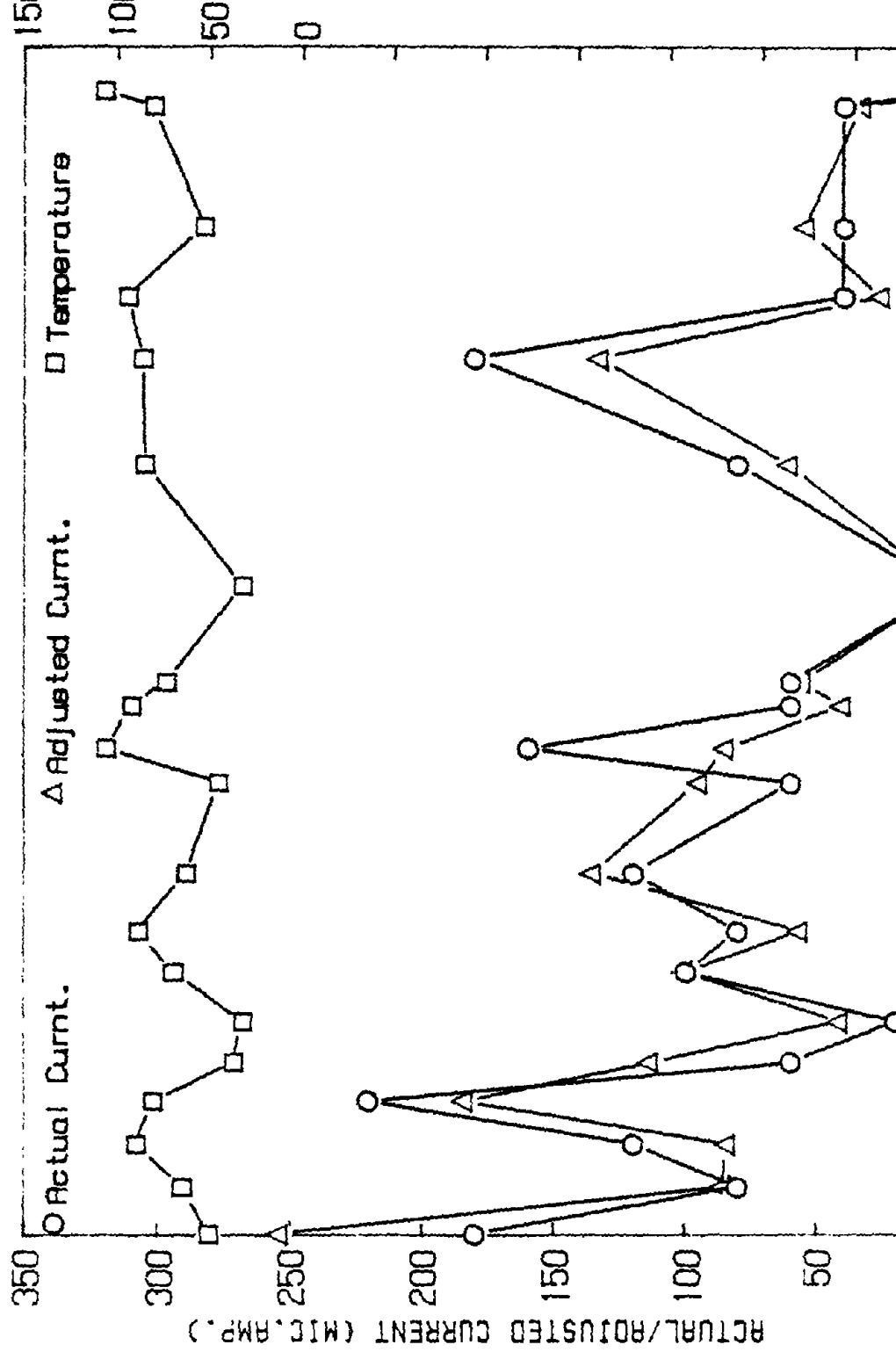
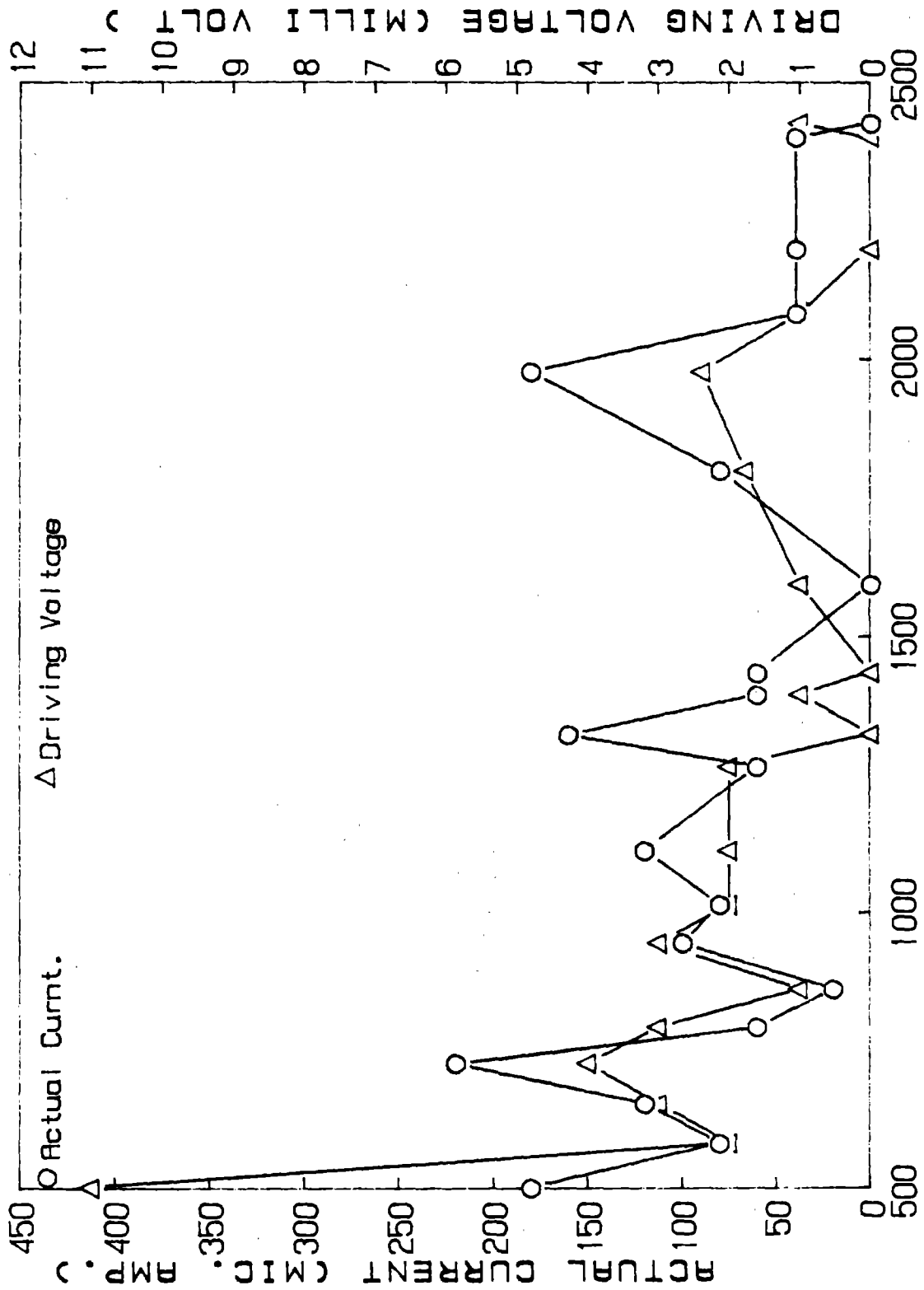


Figure 5. Adjusted current and resistance vs days coupled.

ACTUAL/ADJUSTED CURRENT VS. DAYS COUPLED
 TEMPERATURE VS. DAYS COUPLED
 SLAB NO. 210-419



**ACTUAL CURRENT VS. DAYS COUPLED
DRIVING VOLTAGE VS. DAYS COUPLED**



DAYS COUPLED

Figure 7. Actual current and driving voltage vs days coupled.

AVERAGE TOP/BOTTOM MAT POTENTIAL VS. DAYS COUPLED
AVERAGE POTENTIAL DIFFERENCE VS. DAYS COUPLED
SLAB NO. 219-419

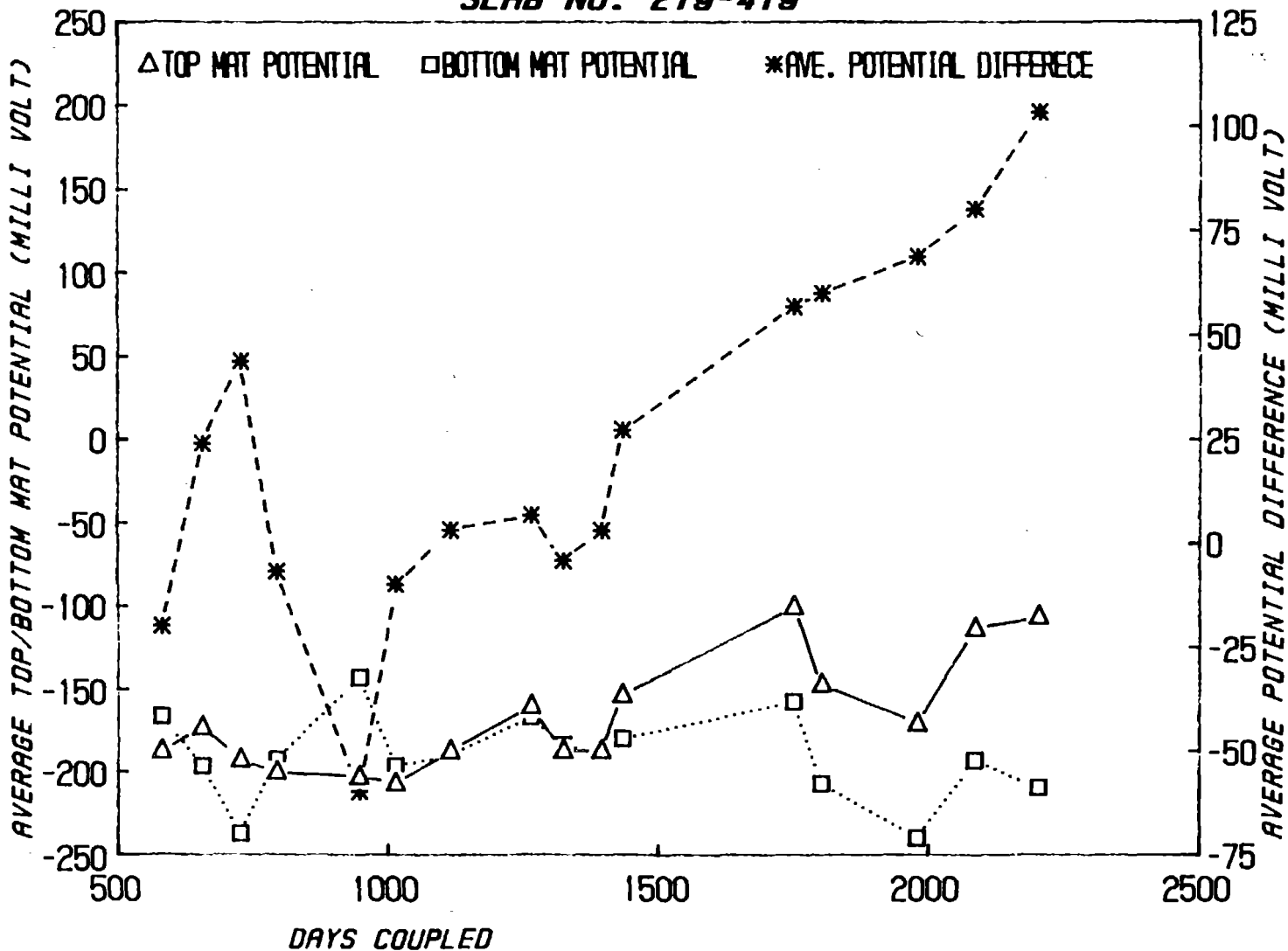


Figure 8. Average top mat, bottom mat and difference potentials vs days coupled.

Table 1. Concrete mixture design.^{1, 2}

Cement	7.0 sacks/yd ³
Water to Cement Ratio	0.53
Fine Aggregate	1160 lbs/yd ³
Coarse Aggregate	1550 lbs/yd ³
Darex AEA	290 ml/yd ³
Unit Weight	138 lb/ft ³
Air Content	7±1.5 percent
Slump	2.0 to 3.0 in

1 Made in 9-ft³ batches.

2 Calcium nitrite slabs contain 18.09 lbs of calcium nitrite dissolved in 43.2 lbs of water. This amount is subtracted from the total water added in the concrete mixture.

Conversions

1 in = 25.4mm

1 ft³ = 0.028m³

1 sack/yd³ = 94 lbs/yd³ = 56.4 Kg/m³

1 lb/yd³ = 0.6 Kg/m³

1 ml/yd³ = 1.3 ml/m³

1 lb/ft³ = 16.02kg/m³

Table 2. Calcium nitrite and control slabs (black steel) @ 2429 days coupled.

Slab No.	2.75% Calcium Nitrite	lbs. Cl ⁻ /Yd ³ in Hardened Concrete	Avg. Driving Voltage mV	Avg. 70 °F Corrosion Current μ A	Weighted Avg. 70 °F Corrosion Current μ A	Avg. 70 °F Mat-to-Mat Resistance ohms	70 °F Iron Consumed grams
(A) Ponded Slabs							
211	No	3.6	7	275	376	16.3	22.82
216	Yes	3.7	0	2	2	11.2	0.09
213	No	7.9	34	1984	2296	13.3	139.19
214	No	6.9	36	2036	2050	13.2	124.28
218*	Yes	8.4	3	145	231	12.4	14.02
219	Yes	8.4	2	88	115	11.0	6.97
220	Yes	11.7	3	95	112	12.4	6.77
221	Yes	10.9	3	115	113	12.3	6.87
222	Yes	13.4	6	241	216	15.3	13.11
223**	Yes	14.3	27	444	476	59.1	28.85
224	Yes	16.7	25	1173	1152	14.6	69.86
225	Yes	16.3	41	2187	2117	13.0	128.34
226	Yes	16.8	40	2566	2591	11.0	157.07
227	Yes	20.2	31	1912	1877	10.9	113.83
215***	No	23.3	51	2865	3566	13.5	216.23
228****	Yes	22.6	58	2034	1663	63.5	100.84
(B) Slabs Not Ponded							
212**	No	0	0	6	7	133	0.42
217	Yes	0	0	0	0.0	13.0	0.0

* Slab may have contained non detectable surface cracks (over rebar) before ponding.

** Resistance measurements indicate these slabs are at least partially debonded between the top and bottom lifts.

*** This slab is severely cracked

**** This slab is debonded between the top and bottom lifts and also severely cracked.

Table 3. Summary of corrosion currents-control (black steel) slabs @ 2429 days coupled.

Control Slab No.	Avg. Cl^- At Top rebar level $\text{lbs Cl}^-/\text{Yd}^3$	Weighted Avg. 70 °F Corrosion Current, μA
211	3.6	376
213, 214	7.5	2173
202, 234	15.6	3652
215*	23.3	3566

* This slab is severely cracked; hence the data for this slab has not been plotted in figure 3.

Table 4. Summary of corrosion currents - nitrite slabs vs. control (black steel) slabs @ 2429 days coupled.

Nitrite Slabs	Avg. Cl ⁻ At Top Rebar Level lbs Cl ⁻ /yd ³ *	Theo. Cl ⁻ to NO ₂ ⁻ Ratio**	Weighted Avg. 70 °F Corrosion Current μ A		Ratio of Currents for No Nitrite/Nitrite
			Nitrite Slabs	No Nitrite Slab***	
216	3.7	0.29	2.0	625	312 to 1
218, 219	8.4	0.67	173	1926	11.1 to 1
220, 221	11.4	0.90	112	2759	24.6 to 1
222, 223****	14.0	1.11	346	3479	10.1 to 1
224, 225	16.4	1.30	1635	4144	2.5 to 1
226, 227	18.5	1.47	2234	4726	2.1 to 1
228****	22.6	1.79	1663	5861	3.5 to 1

* Experimental measured Values of Av. Cl⁻ are from table 6.(5)

** Values of Cl⁻ to NO₂⁻ ratio are from table 9.(5) The nitrite ions are derived from the calcium nitrite admixed in the fresh concrete.

*** Values for weighted average corrosion current for slabs without nitrite were obtained using the least square-fit line in figure 3.

**** Resistance measurements indicate that these slabs are partially debonded between the top and bottom lifts. Also slab 228 is severely cracked and, hence, the measured weighted average corrosion current value may not be accurate.

Table 5. Average electrical half Cell (black steel slabs) potentials.

Slab No.	Variable*	Avg. Electrical Potential mV, CSE		Avg. Potential Difference, mV
		Top Mat	Bottom Mat	
211	No calcium nitrite; 3.6 lbs Cl ⁻ /Yd ³	-111	-76	-35
212	No calcium nitrite; no chloride; no ponding	-154	-38	-116
213	No calcium nitrite; 7.9 lbs Cl ⁻ /Yd ³	-219	-145	-74
214	No calcium nitrite; 6.9 lbs Cl ⁻ /Yd ³	-300	-156	-144
215	No calcium nitrite; 23.3 lbs Cl ⁻ /Yd ³	-393	-289	-104
216	2.75% calcium nitrite; 3.7 lbs Cl ⁻ /Yd ³	-105	-106	+1
217	2.75% calcium nitrite; no chloride; no ponding	-117	-96	-21
218	2.75% calcium nitrite; 8.4 lbs Cl ⁻ /Yd ³	-185	-174	-11
219	2.75% calcium nitrite; 8.4 lbs Cl ⁻ /Yd ³	-174	-191	+17
220	2.75% calcium nitrite; 11.7 lbs Cl ⁻ /Yd ³	-215	-180	-35

Table 5. Average electrical half cell (black steel slabs) potentials (continued).

Slab No.	Variable*	Avg. Electrical Potential mV, CSE		Avg. Potential Difference, mV
		Top Mat	Bottom Mat	
221	2.75% calcium nitrite; 10.9 lbs Cl ⁻ /Yd ³	-181	-189	+8
222	2.75% calcium nitrite; 13.4 lbs Cl ⁻ /Yd ³	-297	-245	-52
223	2.75% calcium nitrite; 14.3 lbs Cl ⁻ /Yd ³	-369	-220	-149
224	2.75% calcium nitrite; 16.7 lbs Cl ⁻ /Yd ³	-370	-284	-86
225	2.75% calcium nitrite; 16.3 lbs Cl ⁻ /Yd ³	-406	-285	-121
226	2.75% calcium nitrite; 16.8 lbs Cl ⁻ /Yd ³	-408	-297	-111
227	2.75% calcium nitrite; 20.2 lbs Cl ⁻ /Yd ³	-418	-291	-127
228	2.75% calcium nitrite; 22.6 lbs Cl ⁻ /Yd ³	-411	-300	-111

* Measured average chloride values between 1/2 - 2-in depth from the top surface of the slabs. This chloride was either added during the mixing of the top lift concrete and/or upper concrete slab surface was ponded with 3 percent salt solution.

Table 6. Average resistance and resistivity.

Slab No.	Variable*	Measurement Period	Average 70 °F MAT-to-MAT Resistance, ohms	Average Resistivity ohms-Cm
211	No calcium nitrite; 3.6 lbs Cl ⁻ /Yd ³	year 1980	10.06	7103
		1983	16.84	11890
		1986	20.84	14715
		80 thru 86	16.30	11509
212**	No calcium nitrite; no chloride; no ponding	year 1980	23.36	16494
		1983	111.6	78828
		1986	209.2	147695
		80 thru 86	133.2	94037
213	No calcium nitrite; 7.9 lbs Cl ⁻ /Yd ³	year 1980	10.20	7203
		1983	14.37	8946
		1986	13.80	9744
		80 thru 86	13.31	9399
214	No calcium nitrite; 6.9 lbs Cl ⁻ /Yd ³	year 1980	10.84	7654
		1983	15.30	10803
		1986	12.45	9078
		80 thru 86	13.21	9327
215	No calcium nitrite; 23.3 lbs Cl ⁻ /Yd ³	year 1980	9.11	6432
		1983	11.53	8141
		1986	17.65	12462
		80 thru 86	13.46	9584
216	2.75% calcium nitrite; 3.7 lbs Cl ⁻ /Yd ³	year 1980	7.14	5042
		1983	11.44	8078
		1986	13.91	9821
		80 thru 86	11.20	7909
217	2.75% calcium nitrite; no chloride; no ponding	year 1980	8.56	6044
		1983	11.85	8368
		1986	16.61	11728
		80 thru 86	12.97	9158
218	2.75% calcium nitrite; 8.4 lbs Cl ⁻ /Yd ³	year 1980	8.10	5719
		1983	12.71	8975
		1986	16.04	11326
		80 thru 86	13.06	9222
219	2.75% calcium nitrite; 8.4 lbs Cl ⁻ /Yd ³	year 1980	7.10	5012
		1983	10.73	7575
		1986	13.51	9538
		80 thru 86	10.97	7745

Table 6. Average Resistance and Resistivity (continued).

Slab No.	Variable*	Measurement Period	Average 70 °F MAT-to-MAT Resistance, ohms	Average Resistivity ohms-Cm
220	2.75% calcium nitrite; 11.7 lbs Cl ⁻ /Yd ³	year 1980	7.80	5507
		1983	12.28	8671
		1986	15.47	10923
		80 thru 86	12.36	8728
221	2.75% calcium nitrite; 10.9 lbs Cl ⁻ /Yd ³	year 1980	7.71	5444
		1983	12.07	8522
		1986	16.10	11368
		80 thru 86	12.32	8699
222	2.75% calcium nitrite; 13.4 lbs Cl ⁻ /Yd ³	year 1980	8.86	6256
		1983	14.70	10379
		1986	20.73	14637
		80 thru 86	18.11	12787
223**	2.75% calcium nitrite; 14.3 lbs Cl ⁻ /Yd ³	year 1980	27.01	19072
		1983	84.96	59989
		1986	29.98	21169
		80 thru 86	58.37	41214
224	2.75% calcium nitrite; 16.7 lbs Cl ⁻ /Yd ³	year 1980	10.39	7336
		1983	15.57	10994
		1986	15.47	10924
		80 thru 86	14.83	10471
225	2.75% calcium nitrite; 16.3 lbs Cl ⁻ /Yd ³	year 1980	10.39	7336
		1983	15.05	10626
		1986	11.74	8290
		80 thru 86	14.51	10245
226	2.75% calcium nitrite; 16.8 lbs Cl ⁻ /Yd ³	year 1980	7.90	5578
		1983	12.44	8784
		1986	11.19	7901
		80 thru 86	11.02	7781
227	2.75% calcium nitrite; 20.2 lbs Cl ⁻ /Yd ³	year 1980	7.63	5387
		1983	12.11	8551
		1986	10.74	7584
		80 thru 86	11.05	7802
228**	2.75% calcium nitrite; 22.6 lbs Cl ⁻ /Yd ³	year 1980	8.49	5995
		1983	10.85	7662
		1986	281.9	199019
		80 thru 86	81.29	57398

* Average value of Cl⁻ at top reinforcing steel mat.

** Partially debonded slabs between the top and bottom lifts.

Table 7. Visual survey summary.

Slab No.	Calcium* Nitrite	lbs Cl ⁻ /Yd ³	Comments
211	0.0	3.6	No cracks; no rust
212	0.0	0	No cracks; no rust
213	0.0	7.9	Moderate amounts of wide cracks, some rust
214	0.0	6.9	Small to medium cracks; no rust
215	0.0	23.3	Large amounts of wide cracks, major rust
216	2.75	3.7	No cracks; no rust
217	2.75	0	No cracks; no rust
218**	2.75	8.4	Fine cracks; rust visible
219	2.75	8.4	No cracks; no rust
220	2.75	11.7	No cracks, one rust spot
221	2.75	10.9	No fine cracks, no rust
222	2.75	13.4	Fine cracks, two rust spots
223	2.75	14.3	Cracks; rust coming from cracks
224	2.75	16.7	Wide cracks; spalls; rust coming from cracks
225	2.75	16.3	Wide cracks; spalls; major rust
226	2.75	16.8	Wide cracks; spalls, major rust
227	2.75	20.2	Wide cracks, spalls, major rust
228	2.75	22.6	Wide cracks, spalls, major rust

* Percentage by weight of cement.

** This slab may have contained surface cracks (over rebar) before ponding.

Table 8. Corrosion current and iron consumed.

 SLAB # : 219-419
 DATA : CORROSION CURRENT & IRON CONSUMED
 VARIABLE : BLACK STEEL, 2.75% CALCIUM NITRITE,
 8.4 LBS CL-/CUB. YD., TOP LIFT

DAYS COUPLED	DRIVING VOLTAGE MILLI V	ACTUAL CURRENT MIC.AMP	ADJ.CUR TO 70F MIC.AMP	ADJ.RES TO 70F OHMS	APPROX. ACTUAL TEMP F	CUMUL. AMP. HOURS	70F-IRON CONSUMED GRAMS
505	11.00	180.00	254.20	7.53	52.00	3.19	3.32
554	4.00	320.00	284.90	8.88	76.30	3.51	3.65
576	3.00	100.00	96.30	9.44	72.00	3.61	3.75
583	2.00	80.00	86.10	11.65	66.10	3.63	3.78
624	2.00	160.00	171.80	9.30	66.20	3.76	3.91
643	0.00	80.00	61.70	11.13	84.40	3.81	3.96
657	3.00	120.00	83.90	11.72	90.00	3.83	3.98
672	4.00	280.00	191.70	10.98	91.30	3.88	4.04
685	6.00	400.00	235.50	11.70	100.20	3.95	4.11
729	4.00	220.00	183.80	11.37	79.90	4.17	4.34
762	5.00	120.00	194.00	9.90	45.30	4.32	4.49
779	2.00	120.00	152.10	10.73	57.50	4.39	4.57
793	3.00	60.00	113.70	8.28	37.60	4.43	4.61
826	1.00	80.00	150.40	8.88	37.90	4.53	4.71
838	2.00	80.00	135.40	8.69	43.00	4.57	4.75
861	1.00	20.00	41.20	8.53	33.60	4.62	4.80
875	4.00	140.00	162.70	8.78	62.00	4.65	4.84
894	3.00	160.00	204.20	8.15	57.10	4.73	4.92
947	3.00	100.00	100.80	9.62	69.60	4.92	5.12
973	3.00	420.00	247.40	10.86	100.20	5.03	5.23
1006	2.00	20.00	22.90	11.07	62.70	5.14	5.35
1013	2.00	80.00	57.00	14.31	88.90	5.15	5.36
1036	2.00	120.00	83.70	13.92	90.20	5.19	5.40
1058	2.00	40.00	39.00	13.96	71.40	5.22	5.43
1114	2.00	120.00	135.10	11.99	63.70	5.34	5.55
1184	2.00	60.00	96.00	9.50	45.80	5.53	5.75
1211	2.00	20.00	33.70	8.97	43.30	5.57	5.79
1266	2.00	60.00	95.10	8.84	46.20	5.66	5.89
1289	2.00	120.00	114.50	9.33	72.50	5.72	5.95
1301	1.00	140.00	107.50	10.15	84.60	5.75	5.98
1322	0.00	160.00	85.40	11.43	106.20	5.80	6.03
1336	2.00	60.00	47.60	10.60	82.80	5.82	6.05
1352	0.00	40.00	28.10	11.80	89.70	5.83	6.06
1370	0.00	0.00	0.00	11.76	77.80	5.84	6.07
1396	1.00	60.00	40.60	12.53	91.90	5.85	6.08
1412	2.00	60.00	60.30	11.45	69.80	5.87	6.10
1434	0.00	60.00	56.00	13.19	73.80	5.90	6.14
1450	2.00	60.00	69.20	13.26	62.40	5.92	6.16
1516	1.00	0.00	0.00	10.75	41.20	5.97	6.21

Table 8. Corrosion current and iron consumed (continued).

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                SLAB # : 219-419
                DATA  : CORROSION CURRENT & IRON CONSUMED
                VARIABLE : BLACK STEEL, 2.75% CALCIUM NITRITE,
                        8.4 LBS CL-/CUB. YD., TOP LIFT
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DAYS COUPLED	DRIVING VOLTAGE MILLI V	ACTUAL CURRENT MIC.AMP	ADJ.CUR TO 70F MIC.AMP	ADJ.RES TO 70F OHMS	APPROX. ACTUAL TEMP F	CUMUL. AMP. HOURS	70F-IRON CONSUMED GRAMS
1596	1.00	0.00	0.00	9.24	32.70	5.97	6.21
1751	0.00	0.00	0.00	14.78	75.80	5.97	6.21
1770	0.00	0.00	0.00	15.33	87.50	5.97	6.21
1801	1.78	80.00	60.90	15.50	85.10	5.99	6.23
1826	2.02	80.00	68.40	14.15	78.60	6.03	6.27
1863	1.85	100.00	89.70	12.82	75.90	6.10	6.34
1979	2.40	180.00	133.20	10.64	86.70	6.41	6.67
2008	1.60	80.00	67.50	10.07	19.30	6.48	6.74
2050	0.00	0.00	0.00	12.91	85.10	6.51	6.77
2085	1.00	40.00	26.00	15.69	94.30	6.52	6.78
2107	0.00	0.00	0.00	15.47	79.10	6.53	6.79
2165	0.00	40.00	33.90	15.69	79.10	6.55	6.81
2201	0.00	40.00	54.20	15.49	54.00	6.59	6.85
2267	0.00	0.00	0.00	12.11	44.50	6.63	6.90
2402	0.00	40.00	32.90	13.87	80.70	6.68	6.95
2413	1.00	40.00	31.70	15.27	82.80	6.69	6.96
2429	1.00	0.00	0.00	16.23	106.60	6.70	6.97
AVERAGE	1.90	93.57	87.89	11.61	70.27		
WEIGHTED AVE.					115		
INITIAL :							
TOTAL NUMBER OF READINGS:					56		

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Table 9. Electric potentials.

SLAB # : 219-419
 DATA : ELECTRIC POTENTIALS
 VARIABLE : BLACK STEEL, 2.75% CALCIUM NITRITE,
 8.4 LBS CL-/CUB. YD., TOP LIFT

DAYS COUPLED	PROB #1 POTENT. MILLI- VOLTS	TOP MILLI				BOTTOM MILLI				AVERAGE POT. DIFF MILLI VOLTS
		1	2	3	AVERAGE	1	2	3	AVERAGE	
505	-	-	-	-	-	-	-	-	-	-
554	-	-200	-180	-190	-190	-200	-170	-200	-190	0
576	-	-210	-200	-220	-210	-180	-170	-200	-183	-27
583	-	-190	-180	-190	-187	-180	-160	-160	-167	-20
624	-	-150	-150	-210	-170	-200	-180	-210	-197	27
643	-	-170	-170	-150	-163	-	-	-	-	-
657	-	-190	-180	-150	-173	-220	-190	-180	-197	24
672	-	-210	-210	-210	-210	-	-	-	-	-
685	-	-240	-230	-260	-243	-230	-210	-220	-220	-23
729	-	-220	-200	-160	-193	-240	-260	-210	-237	44
762	-	-200	-200	-160	-187	-210	-180	-190	-193	6
779	-	-200	-190	1	-130	-210	-180	-190	-193	63
793	-	-210	-180	-210	-200	-200	-180	-200	-193	-7
826	-	-190	-180	-180	-183	-190	-170	-180	-180	-3
838	-	-200	-200	-210	-203	-200	-190	-200	-197	-6
861	-	-	-	-	-	-	-	-	-	-
875	-	-210	-240	-270	-240	-210	-190	-220	-207	-33
894	-	-260	-250	-280	-263	-220	-190	-230	-213	-50
947	-	-210	-200	-200	-203	-110	-150	-170	-143	-60
973	-	-180	-220	-190	-197	-220	-170	-190	-193	-4
1006	-	-170	-150	-130	-150	-170	-150	-160	-160	10
1013	-	-220	-210	-190	-207	-220	-190	-180	-197	-10
1036	-	-220	-220	-200	-213	-220	-190	-180	-197	-16
1058	-	-210	-190	-180	-193	-220	-180	-170	-190	-3
1114	-	-190	-200	-170	-187	-160	-200	-210	-190	3
1184	-	-140	-190	-120	-150	-180	-160	-140	-160	10
1211	-	-	-	-	-	-	-	-	-	-
1266	-	-140	-190	-150	-160	-190	-150	-160	-167	7
1289	-	-170	-190	-170	-177	-180	-140	-150	-157	-20
1301	-	-180	-190	-180	-183	-190	-160	-160	-170	-13
1322	-	-150	-230	-180	-187	-200	-180	-170	-183	-4
1336	-	-200	-160	-210	-190	-170	-170	-180	-173	-17
1352	-	-170	-190	-190	-183	-170	-170	-190	-177	-6
1370	-	-170	-160	-170	-167	-180	-150	-180	-170	3
1396	-	-190	-200	-170	-187	-200	-190	-180	-190	3
1412	-	-210	-150	-180	-180	-190	-170	-170	-177	-3
1434	-	-170	-110	-180	-153	-190	-170	-180	-180	27
1450	-	-180	-120	-140	-147	-180	-160	-190	-177	30

Table 9. Electric potentials (continued).

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*****
SLAR # : 219-419
DATA : ELECTRIC POTENTIALS
VARIABLE : BLACK STEEL, 2.75% CALCIUM NITRITE,
          8.4 LBS CL-/CUB. YD., TOP LIFT
*****

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DAYS COUPLED	PROB #1 POTENT. MILLI VOLTS	TOP MILLI				BOTTOM MILLI				AVERAGE POT. DIFF MILLI VOLTS		
		1	2	3	AVERAGE	1	2	3	AVERAGE			
1516	-	-	-	-	-	-	-	-	-	-		
1596	-	-	-	-	-	-	-	-	-	-		
1751	-	-60	-150	-90	-100	-170	-150	-150	-157	57		
1770	-	-170	-190	-100	-153	-200	-170	-170	-180	27		
1801	-	-50	-210	-180	-147	-240	-180	-200	-207	60		
1826	-	-70	-240	-140	-150	-250	-190	-200	-213	63		
1863	-	-50	-210	-130	-130	-240	-210	-220	-223	93		
1979	-	-129	-224	-160	-171	-240	-240	-240	-240	69		
2008	-	-100	-200	-120	-140	-270	-240	-220	-243	103		
2050	-	-30	-200	-130	-120	-220	-220	-210	-217	97		
2085	-	-20	-200	-120	-113	-200	-190	-190	-193	80		
2107	-	-162	-194	-184	-180	-220	-200	-190	-203	23		
2165	-	-80	-170	-140	-130	-220	-200	-200	-207	77		
2201	-	-50	-160	-110	-107	-220	-210	-200	-210	103		
2267	-	-50	-140	-70	-87	-180	-170	-170	-173	86		
2402	-	-74	-238	-243	-185	-	-	-	-	-		
2413	-	-100	-270	-266	-212	-	-	-	-	-		
2429	-	-132	-259	-252	-214	-	-	-	-	-		
AVERAGE						-174					-191	18
TOTAL NUMBER OF READINGS:						56						

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Table 10. Resistance and resistivity.

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*****
SLAB # : 219-419
DATA : RESISTANCE & RESISTIVITY
VARIABLE : BLACK STEEL, 2.75% CALCIUM NITRITE,
          8.4 LBS CL-/CUB. YD., TOP LIFT
*****

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DATE DATA TAKEN	DAYS COUPLED	MAT-MAT R70F OHMS	CHANGE MAT-MAT PERCENT
10-08-80	0	8.40	0
10-10-80	2	7.80	-7
10-16-80	8	7.60	-10
10-22-80	14	7.00	-17
11-07-80	30	6.60	-21
11-21-80	44	6.10	-27
12-08-80	61	6.20	-26
AVERAGE FOR YEAR 80		7.10	
RESISTIV. CONST		706	
AVERAGE RESISTI. FOR YEAR 80		5012	
01-22-81	106	5.60	-33
02-26-81	141	15.90	89
03-26-81	169	9.20	10
04-27-81	201	7.40	-12
07-07-81	272	9.40	12
10-09-81	366	9.80	17
AVERAGE FOR YEAR 81		9.55	
RESISTIV. CONST		706	
AVERAGE RESISTI. FOR YEAR 81		6838	

Table 10. Resistance and resistivity (continued).

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*****
SLAB # : 219-419
DATA : RESISTANCE & RESISTIVITY
VARIABLE : BLACK STEEL, 2.75% CALCIUM NITRITE,
           8.4 LBS CL-/CUB. YD., TOP LIFT
    
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DATE DATA TAKEN	DAYS COUPLED	MAT-MAT R70F OHMS	CHANGE MAT-MAT PERCENT
02-25-82	505	7.53	-10
04-15-82	554	8.88	6
05-07-82	576	9.44	12
05-14-82	583	11.65	39
06-24-82	624	9.30	11
07-13-82	643	11.13	33
07-27-82	657	11.72	40
08-11-82	672	10.98	31
08-24-82	685	11.70	39
10-07-82	729	11.37	35
11-09-82	762	9.90	18
11-26-82	779	10.73	28
12-10-82	793	8.28	-1
AVERAGE FOR YEAR 82		10.20	
RESISTIV. CONST		706	
AVERAGE RESISTI. FOR YEAR 82		7201	

01-12-83	826	8.88	6
01-24-83	838	8.69	3
02-16-83	861	8.53	2
03-02-83	875	8.78	5
03-21-83	894	8.15	-3
05-13-83	947	9.62	15
06-08-83	973	10.86	29
07-11-83	1006	11.07	32
07-18-83	1013	14.31	70
08-10-83	1036	13.92	66
09-01-83	1058	13.96	66
10-27-83	1114	11.99	43
AVERAGE FOR YEAR 83		10.73	
RESISTIV. CONST		706	
AVERAGE RESISTI. FOR YEAR 83		7575	

Table 10. Resistance and resistivity (continued).

SLAB # : 219-419 DATA : RESISTANCE & RESISTIVITY VARIABLE : BLACK STEEL, 2.75% CALCIUM NITRITE, 8.4 LBS CL-/CUB. YD., TOP LIFT			
DATE DATA TAKEN	DAYS COUPLED	MAT-MAT R70F OHMS	CHANGE MAT-MAT PERCENT
01-05-84	1184	9.50	13
02-01-84	1211	8.97	7
03-27-84	1266	8.84	5
04-19-84	1289	9.33	11
05-01-84	1301	10.15	21
05-22-84	1322	11.43	36
06-05-84	1336	10.60	26
06-21-84	1352	11.80	40
07-09-84	1370	11.76	40
08-04-84	1396	12.55	49
08-20-84	1412	11.45	36
09-11-84	1434	13.19	57
09-27-84	1450	13.26	58
12-02-84	1516	10.75	28
AVERAGE FOR YEAR 84		10.97	
RESISTIV. CONST		706	
AVERAGE RESISTI. FOR YEAR 84		7745	
02-20-85	1596	9.24	10
07-25-85	1751	14.78	76
08-13-85	1770	15.33	83
09-13-85	1801	15.50	85
10-08-85	1826	14.15	68
11-14-85	1863	12.82	53
AVERAGE FOR YEAR 85		13.64	
RESISTIV. CONST		706	
AVERAGE RESISTI. FOR YEAR 85		9630	

Table 10. Resistance and resistivity (continued).

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*****
SLAB # : 219-419
DATA : RESISTANCE & RESISTIVITY
VARIABLE : BLACK STEEL, 2.75% CALCIUM NITRITE,
          8.4 LBS CL-/CUB. YD., TOP LIFT
-----
DATE          DAYS          MAT-MAT          CHANGE
DATA          COUPLED        R70F            MAT-MAT
TAKEN                                     OHMS            PERCENT
-----
03-10-86      1979                    10.64           27
04-08-86      2008                    10.07           20
05-20-86      2050                    12.91           54
06-24-86      2085                    15.69           87
07-16-86      2107                    15.47           84
09-12-86      2165                    15.69           87
10-18-86      2201                    15.49           84
12-23-86      2267                    12.11           44
-----
AVERAGE FOR YEAR 86                    13.51
RESISTIV. CONST                          706
AVERAGE RESISTI. FOR YEAR 86            9538
-----

05-07-87      2402                    13.87           65
05-18-87      2413                    15.27           82
06-03-87      2429                    16.23           93
-----
AVERAGE FOR YEAR 87                    15.12
RESISTIV. CONST                          703
AVERAGE RESISTI. FOR YEAR 87            10674
-----

***** AVERAGE FOR ALL YEARS READINGS *****
-----
AVERAGE                    10.97
INITIAL :                   8.40
RESISTIV. CONST             703
AVERAGE RESISTI.           7745
TOTAL NUMBER OF READINGS    69
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