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TIME-TO-CORROSION OF REINFORCING STEEL IN CONCRETE SLABS

Vol. 4. Galvanized Reinforcing Steel

December 1981

Interim Report

U.S. Department of Transportation
Federal Highway Administration

Offices of Research & Development
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16. Abstract
Four-ft. by 5-ft. by 6-inch (1.2m X 1.5m X 0.15m) reinforced concrete slabs were fabricated, cured and subjected to 7 years of daily salting at an outdoor exposure yard. Subsequently, the slabs were modified and instrumented to allow direct measurement of the corrosion current flowing between the top and bottom mats of reinforcing steel and other characteristics of the corrosion process.

Comparison of the performance of galvanized reinforcing steel and conventional black steel in the slabs indicated the following:

1. Galvanized reinforcing steel is subject to the same type of macroscopic (galvanic) corrosion in salt-contaminated concrete, as black steel.
2. There was no benefit from the use of all galvanized reinforcing steel in a 0.40 water-cement ratio concrete.
3. Galvanizing all the reinforcing steel in a 0.50 water-cement ratio concrete resulted in slightly lower corrosion rates, whereas galvanizing only the top mat reinforcing steel was very detrimental, resulting in corrosion rates twice as high as those for all black steel.
4. The lowest corrosion rates measured in this comparative study of black and galvanized steel were those for the slab containing all black steel and a 0.40 water-cement ratio concrete.

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concrete, corrosion, reinforcing steel, galvanizing, bridge deck, corrosion rate, macrocell, galvanic cell

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FOREWORD

This report presents the findings of an outdoor exposure study of concrete slabs containing black reinforcing steel and galvanized reinforcing steel. The tests were performed under conditions which simulate those found in typical highway bridge decks. A solution of water and deicing salt was ponded on the surface of the slabs for several years to produce a concrete contaminated with chloride ions. The ponding was then discontinued, the slabs were modified and instrumented so that the corrosion and deterioratio could be monitored. The performance of the different slabs are compared.

The report will be of interest to bridge engineers in the snow belt where deicing salts are applied to the pavements, and to other design, materials, and corrosion engineers concerned with bridges and hydraulic structures along the coasts. Technically, it shows that corrosion will occur under proper conditions when black or galvanized steel are used solely or in combination. Hence, positive steps must be taken to attain the design lives of structures.

Sufficient copies of the report are being distributed by FHWA Bulletin to provide a minimum of two copies to each FHWA regional office, one copy to each FHWA division office and two copies to each State highway agency. Direct distribution is being made to the division offices. Additional copies for the public are available from the National Technical Informatio Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

Charles F. Scheffey
Director, Office of Research

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Introduction

The major bridge deck deterioration problem is delamination of the concrete near the level of the top mat of reinforcing steel and the subsequent spalling of the surface concrete. Research has shown that the most prevalent cause of this distress is corrosion of the reinforcing steel due to the intrusion of chlorides into the concrete from repeated deicer applications for snow and ice removal. Similar problems also exist in reinforced concrete members exposed to seawater or other chemical environments.

One suggested solution to these problems is galvanized reinforcing steel. To test the hypothesis, the outdoor exposure testing of concrete slabs containing galvanized reinforcing steel was included in the Federal Highway Administration's Time-to-Corrosion studies initiated in 1971.

The report documents the findings of 10 years of comparative testing of large slabs containing conventional black steel and slabs containing galvanized reinforcing bars.

Fabrication and Testing

Four 4-ft. by 5-ft. by 6-inch (1.2m X 1.5m X 0.15m) concrete slabs were constructed using galvanized reinforcing steel in 1971 as part of the Federal Highway Administration's Time-to-Corrosion study (1,2). Over 100 other slabs containing black steel reinforcement were also fabricated in 1971. The slabs were cured for 6 weeks and then placed on 3-ft (0.9m) posts at the FHWA outdoor exposure yard at the Fairbank Highway Research Station, McLean, Virginia. All slabs contained a top mat of reinforcing steel consisting of No. 4 rebar on 12-inch (0.30m) centers in the 5-ft (1.5m) direction and two No. 4 cross bars in the 4-ft (1.2m) direction, (one 12 inches (0.30m) from each slab edge). No bottom reinforcing steel was included. Table 1 provides the fabrication data on the 12 slabs (4 galvanized and 8 black steel) included in this substudy. All of these slabs have 1-inch (25mm) cover over the reinforcing steel and were subjected to daily ponding to a 1/16-inch (2mm) depth with a 3 percent NaCl solution during the period from late 1971 through 1978. At that time, ponding was discontinued and, since then, all slabs are only subjected to natural weathering at the outdoor exposure yard.

All slabs were evaluated periodically using electrical potential measurements, chloride analyses, and delamination and visual surveys. Also in 1974, 1 galvanized-rebar slab and 1 black-steel slab were cut in half and one-half of each slab was broken apart to allow a visual examination of the rebar. The remaining half of each slab continued under test.

The 1974 autopsies of the 2 half slabs (w/c=0.50) found 4 areas of significant corrosion on the black steel rebar, but only 1 area of significant corrosion on the galvanized rebar. In that area, the galvanized coating was completely lost and steel corrosion was obviously occurring. However, in all other areas significant amounts of zinc remained.

Table 2 provides a summary of the results of the evaluations performed on the slabs through 1979. Two other slabs, with black steel, which were made at the same time but were never salted, are also included for comparison. The no-salt slabs remained undamaged throughout the test. For the salted slabs, by 1974 (830 daily saltings), chloride sampling of various 0.40 and 0.50 water cement ratio slabs (2) showed significant quantities of chloride at the 1.0-inch (25mm)

TABLE 1 1971 Slab Fabrication Data

	Concrete Slab Description								
Slab No.	W/C	CF (bags/yd^3) 1/	Cover (in) 2/	Special	Date Made('71)	Weather 3/	Conc. Temp 3/	In-Place Density 4/	Air Cont. (Percent)
105-79	0.40	7.00	1.0	Galvanized	Nov. 10	Cloudy, 39F	55F	143.8	5.5
1-80	0.40	7.00	1.0	Galvanized	Sept.22	- , 64F	71F	144.0	6.5
54-81	0.50	7.00	1.0	Galvanized	Oct. 18	Cloudy, 56F, RH=72%	64F	141.8	5.8
113-82	0.50	7.00	1.0	Galvanized	Nov. 11	Cloudy, 42F	57F	142.3	6.8
9-39	0.40	7.00	1.0	-	Sept.24	Sunny, 71F	74F	143.5	5.6
87-40	0.40	7.00	1.0	-	Nov. 8	Sunny, 37F	54F	144.6	6.8
72-7	0.50	7.00	1.0	-	Oct. 28	Foggy, 56F	63F	143.1	6.2
99-15	0.50	8.00	1.0	Compacted*	Nov. 9	Sunny, 33F	56F	134.3	5.9
21-105	0.50	7.00	1.0	-	Sept.30	Cloudy, 65F RH=72%	68F	141.5	6.2
90-112	0.50	7.00	1.0	Aggre.Prop.**	Nov. 5	Sunny, 40F	47F	133.7	6.0
77-33	0.50	7.00	1.0	No Salt	Nov. 1	Cloudy,70F RH=82%	70F	141.5	5.8
114-3	0.40	7.00	1.0	No Salt	Nov. 11	Cloudy, 44F	57F	144.4	6.2

Notes: *"Compacted" means the surface was steel troweled with downward hand pressure.

** "Aggre. Prop." means the sand/stone ratio in the concrete mix was altered.

Previous data (1,2) showed that these variables had no significant effect on performance.

In-place densities were measured with a direct transmission nuclear gage and are in pounds per cubic foot.

1/ 1 bag/yd^3 = 1.31 bags/m^3

2/ 1in = 25mm

3/ C= 5/9(F-32)

4/ 1 lb/ft^3= 16.0 kg/m^3

TABLE 2. Findings of Condition Surveys of 1974 and 1979

Slab Number	Concrete W/C	Rebar	Range of Electrical Potentials mV CSE	Survey Findings for Year Indicated							
				1974				1979			
				Rust Stains	Cracking	Delamination	Spalling	Rust Stains	Cracking	Delamination	Spalling
105-79	0.40	Galvanized	-140 to -700	No	Very Fine	No	No	Yes	Very fine	No	Yes (1)
1-80	0.40	Galvanized	-200 to -540	No	Very Fine	No	No	Yes	Very fine*	No	No
9-39	0.40	Black Steel	-100 to -490	No	No	No	No	No	No	No	No
87-40	0.40	Black Steel	-100 to -360	No	No	No	No	No	No	No	No
113-82	0.50	Galvanized	-200 to -600	No	No	No	No	No	Yes (short)	No	No
54-81 (1)	0.50	Galvanized	-100 to -590	No	No	No	No	Yes (edge)	No	No	No
99-15	0.50	Black Steel	-210 to -400	No	No	No	No	No	Yes	No	No
90-112	0.50	Black Steel	-130 to -400	No	No	No	No	Yes	No	No	No
21-105	0.50	Black Steel	-110 to -500	Yes	No	No	No	Yes	Yes	No	Yes (1)
72-7 (1)	0.50	Black Steel	-240 to -410	Yes	No	No	No	Yes	Yes	No	No
114-3	0.40	No Salt, Black Steel	-10 to -240	No	No	No	No	No	No	No	No
67-33	0.50	No Salt, Black Steel	0 to -270	No	No	No	No	No	No	No	No

(1) These slabs were cut in half in 1974 and one-half was demolished to allow examination of the rebar.

* Removal of concrete from a 4-inch long area over a bar at one end of the slab, revealed a corroded galvanized bar with red rust showing. Remaining cracking on this slab is very, very fine.

level (average = 1.6 lbs Cl^-/yd^3 ($1.0 kg/m^3$) for w/c = 0.40 concrete and 11.4 lbs Cl^-/yd^3 ($6.8 kg/m^3$) for w/c = 0.50 concrete) and, thus, active black steel corrosion would be expected. Electrical potentials generally indicated active corrosion, or they were in the uncertain area for the salted black steel slabs. Potentials for galvanized rebar slabs were generally more negative than those measured on the black steel slabs. No delamination or spalling was found in 1974 on any of the slabs while the only cracking was very fine cracking found on the 0.40 w/c galvanized slabs. Red rust stains were found on 2 of the salted w/c = 0.50 black steel slabs only.

In 1979, rust stains were visible on 3 of the 4 salted (w/c= 0.50) black steel slabs as well as 2 of the galvanized rebar slabs (1 with w/c = 0.40 and 1 with w/c = 0.50). Cracking was generally more prevalent on the salted w/c = 0.50 black steel slabs than on the galvanized slabs. No delamination was found, but 2 small spalls were present (one on a w/c = 0.40 galvanized rebar slab and 1 on a salted w/c = 0.50 black steel slab). Also, concrete was removed from a 4-inch (100mm) long area over a bar at one end of the other 0.40 water-cement ratio slab with galvanized rebar. A very fine crack was visible at the removal location. Exposure of the galvanized rebar revealed red rusting, but no significant section loss.

Thus, in general, the data indicate that for the salted 0.50 water cement ratio concrete, the galvanized rebar slabs were performing better than those with black steel. Conversely, for the salted 0.40 water cement ratio concrete slabs, the black steel slabs appeared to be in better condition than their galvanized rebar counterparts.

Although the above data are valuable, they provide little information on the rate of corrosion and, thus, service life projections are very difficult.

In 1979 and 1980, new quantitative information on the corrosion process in concrete was developed (3). These data showed that the rate of corrosion is affected by many factors other than chloride content after the threshold chloride value is exceeded and that macroscopic corrosion cells (those in which the anode and cathode are separated by several inches or more) were of much greater severity than microscopic corrosion cells (i.e., many tiny anodes and cathodes co-existing along the steel but not interacting with each other over long distances). Fortunately, because of the outdoor storage of the slabs and the use of multibar large slabs, the original time-to-corrosion studies constitute valid corrosion tests of reinforcement in concrete. Macroscopic anodes and cathodes exist on the top mat rebars and the wetting and drying and temperature cycling results in relatively high corrosion rates in chloride contaminated concrete. However, there was one major aspect of the deicing salt area bridge deck situation which was lacking; the slabs did not contain a bottom mat of reinforcement electrically coupled to the top mat. Previous data for black steel in concrete projected that a large macroscopic corrosion cell would be set up between a bottom rebar mat in chloride-free concrete and a top rebar mat in chloride-contaminated concrete. Thus, the rebar in the existing slabs, as originally constructed, was probably corroding at a slower rate than the rebar in a chloride-contaminated bridge deck. Further, it was unknown whether or not such a corrosion macrocell would develop between galvanized rebar in chloride contaminated concrete and galvanized steel in chloride-free concrete. Such information was essential to allow complete evaluation of the product.

To develop information, and simultaneously provide a direct measure of the macrocell corrosion rate, bottom mats of reinforcing steel were placed in a 2.5-inch (64mm) lift of chloride-free concrete under each slab. Briefly, the "underlay" process involved the following steps:

(1) Each slab was turned upside down and what had been the bottom of the slab was sandblasted to expose at least 50 percent of the coarse aggregate.

(2) A 2.5-inch (6.4mm) high form was placed around the slab and a bottom mat of reinforcing steel (7 No. 5 bars in the 5-ft. (1.5m) direction and 3 No. 4 bars in the 4-ft (1.2m) direction) was positioned 3/4-inch (19mm) above the existing slab bottom. Lead wires were attached to the rebars and brought outside the slab; thermocouples were attached to various rebars to facilitate temperature measurement.

(3) A 2.5-inch (64mm) lift of chloride-free concrete was placed. The water-cement ratio of the underlay concrete for each slab matched that used originally in 1971 for that slab, as did the aggregate sources and proportions. A vibrating screed was used to consolidate the concrete and after wood floating, the concrete was cured for 14 days using wet burlap and polyethylene.

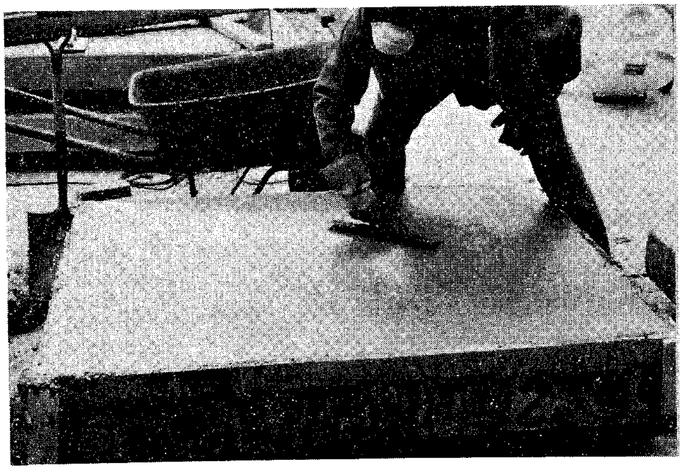
(4) The slabs were then turned back over and placed on 3-ft (0.9m) posts. Several months of such storage were allowed to permit the establishment of a normal bridge deck type moisture gradient within the 8.5-inch (216mm) thick slabs. During this time period, new lead wires and thermocouples were installed on the top mat rebars.

(5) Testing was initiated by coupling the 2 rebar mats together (i.e., the lead wires from the top mat rebars were joined with those from the bottom rebar mats). Because no direct mat-to-mat metallic contacts exist within the concrete, all electrons generated by the macrocell corrosion process must flow through the lead wires. Thus, a direct measure of the macrocell corrosion rate is obtained.

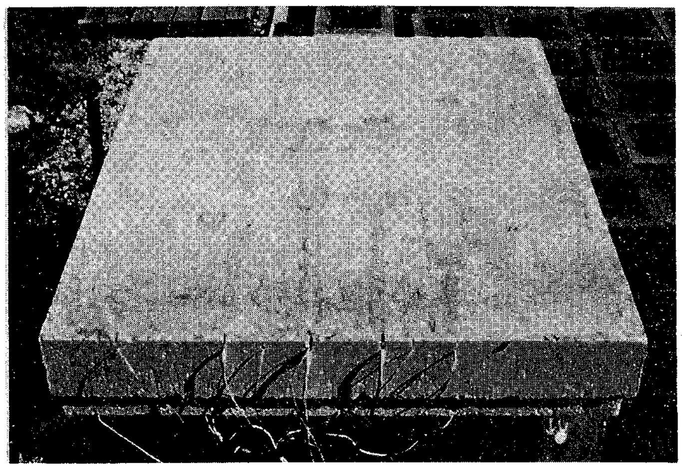
Figure 1 includes several photographs of the underlay process as well as a photograph of the instrumentation interface box utilized to couple the rebar mats and facilitate measurement of the corrosion currents and other necessary parameters.

Because of the length of time required to accomplish all the above operations and other rate of corrosion studies being performed at our outdoor exposure yard, only 7 of the 10 salted slabs previously discussed and 1 no-salt slab were underlaid in sufficient time for use in this study. The 0.50 water cement ratio black steel slabs were underlaid in 1979 because of the need for controls in another substudy while the remaining slabs were underlaid in 1980. Table 3 provides data on each of the underlays, as well as a listing of the various rebar combinations under test. Note that 2 different water-cement ratio concretes (0.40 and 0.50) are under test as well as slabs in which all the reinforcing steel is galvanized and a slab in which only the top mat rebar is galvanized.

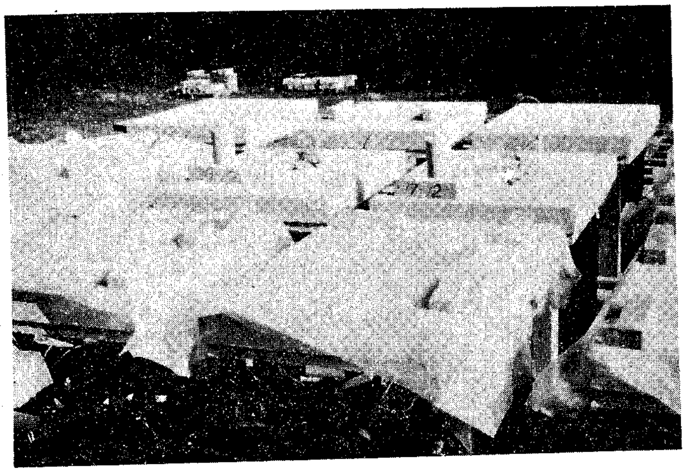
To obtain the desired rate of corrosion comparison between galvanized reinforcing steel and black steel, the corrosion currents were measured periodically during the 6-month period from April through September 1981. This provided corrosion rate data during the relatively cool spring and early fall as well as during the hot summer. Other data obtained include the macrocell driving voltage, the 1,000-cycle AC mat-to-mat resistance and the concrete temperature (at the top-mat level, at slab mid-depth and at the bottom-mat level). Electrical potentials of the top mat rebar as well as those on the bottom-mat rebar were also measured periodically.



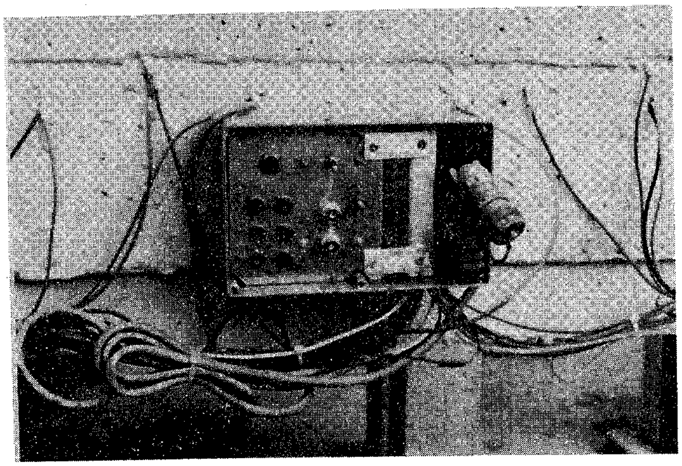
Steel trowel finishing of the "underlay" concrete



Top surface of slab with new lead wires and instrumentation installed and previous core holes patched (complete instrumentation is shown; some slabs in this study received only partial top mat instrumentation)

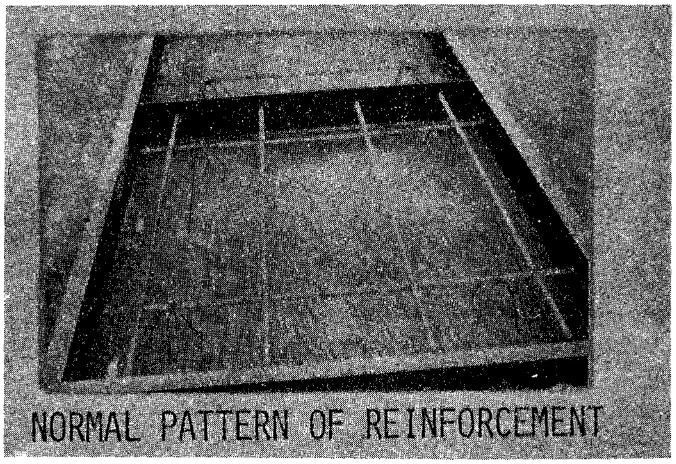


Modified Slabs on stands at outdoor test site

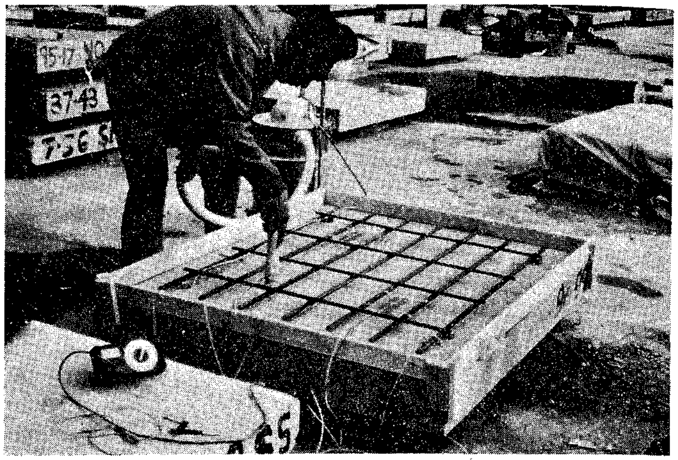


Instrumentation interface box installed on a typical completed slab. (This slab had also received an overlay as part of another study).

Figure 1 (continued) Slab Modification and Instrumentation

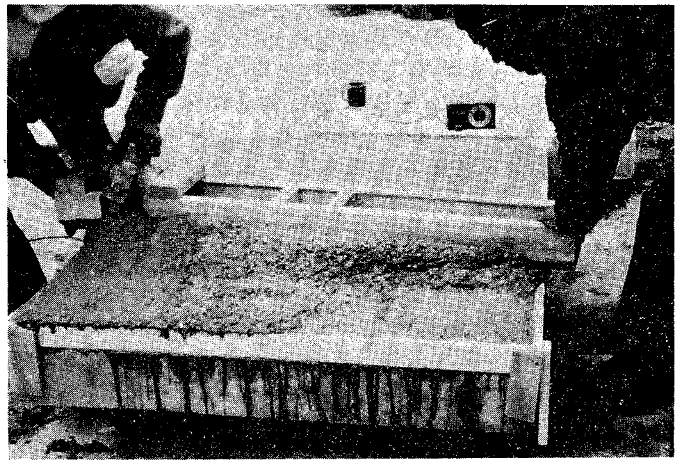


Top Mat Reinforcing
Steel in each original (1971)
slab (from reference 1)



Bottom mat of reinforcing
Steel in place

11 cubic foot (0.3m^3) mixer
at test yard



"Underlay concrete
consolidation

Figure 1. Slab Modification and Instrumentation

TABLE 3 SLAB MODIFICATION DATA

Slab Number	Concrete Water-Cement Ratio	Reinforcing Steel Top Mat	Reinforcing Steel Bottom Mat	Date Underlaid	Date Mats Coupled	Top Mat Rebar Chloride Content[1] lbs Cl /yd^3
54-81	0.50	Galvan.	Galvan.	10-10-80	4-2-81	11.7
113-82	0.50	Galvan.	Black	9-30-80	4-2-81	10.9
90-112	0.50	Black	Black	10-29-79	2-13-80	24.8
99-15	0.50	Black	Black	10-30-79	2-14-80	21.4
21-105	0.50	Black	Black	11-8-79	5-16-80	15.7
77-38	0.50	Black	Black	11-14-79	11-1-80	0.5
105-79	0.40	Galvan.	Galvan.	11-5-80	4-2-81	7.5
9-39	0.40	Black	Black	11-5-80	4-2-81	7.9

[1] Based on one sample obtained and analyzed in accordance with AASHTO T-260.

1lb/yd^3 = 0.6 kg/m^3

Rate of Corrosion Findings

Table 4 summarizes the rate of corrosion data obtained on the slabs. Included are data on:

(1) Average Macrocell Corrosion Current - This is a direct measure of the electrons released by the corrosion process and flowing to the bottom rebar mat for oxygen reduction. As noted in the discussion above, concrete temperature has a significant effect on corrosion current (rate). This effect has been shown (3) to be due primarily to the effect of temperature on concrete resistivity. Also, it has been shown that the corrosion current measured at any given field temperature can be adjusted to another temperature to compensate for differing concrete resistivities using the formula:

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

where i_1 = corrosion current at temperature T_1.

where i_2 = corrosion current measured at temperature T_2.

where T_2 = average temperature of the concrete between the macro-anode and macro-cathode (in degrees Kelvin).

where T_1 = temperature (in degrees Kelvin) that one desires to know the corrosion current.

70 F.(21 C) was chosen as the desired temperature in this study and all measured currents were adjusted to a concrete resistivity corresponding to that temperature.

(2) Average Macrocell Driving Voltage - This is the polarized driving voltage of the corrosion cell measured in the instant-off mode (i.e. an instant after uncoupling the rebar mats) to eliminate iR drop errors. If no corrosion macrocell developed, the driving voltage would be zero. At constant corrosion circuit resistance, the higher the driving voltage, the higher the rate of corrosion.

(3) Mat-to-Mat AC Electrical Resistance - This measurement, made using a 1,000 cycle AC signal after uncoupling the mats and the measurement of electrical potentials, provides an indication of concrete resistivity when black steel, or rebar coated with a metallic material which adds little circuit resistance, is used. The mats are recoupled immediately after making this measurement. Tests in solutions of known resistivity were used to define a resistance-to-resistivity conversion factor (660 for 20 ft.^{2} (1.9m^2) slabs and 376 for the 10 ft^2 (0.9m^2) slabs). Also, this testing showed that the presence of a zinc coating on the rebar had no significant effect on the measurement. In

TABLE 4

Summary of Macro-Cell Corrosion Data

April 2 to September 28, 1981

Slab Number	Variable	Average Driving Voltage mV	Ave. 70 F.[1] Corrosion Current, μA/ft^2	Weighted Ave. 70 F. Corrosion Current, μA/ft^2	70 F. Metal Consumed, grams/ft^2	Ave. 70 F. Mat to Mat Resistivity, Ω - cm
W/C = 0.50 Concrete Salted						
54-81	All Galvan.	47.5	97.1 [2]	102.5 [2]	0.54[3]	14,645
113-82	Top Mat Galvan.	137.4	150.9	165.7	0.87	22,140
90-112	Black Steel	71.3	77.7	76.0	0.34	22,850
99-115	Black Steel	84.7	167.6	164.4	0.73	13,910
21-105	Black Steel	93.1	217.6	214.6	0.95	11,946
W/C = 0.50 Concrete - No Salt						
77-38	Black Steel	0	0	0	0	20,310
W/C - 0.40 Concrete Salted						
105-79	All Galvan.	36.1	26.4	25.2	0.135	36,194
9-39	Black Steel	22.2	19.8	21.3	0.095	28,840

[1] C= 5/9(F-32)

[2] 1μA/ft^2=10.8μA/m^2

[3] 1g/ft^2=10.8g/m^2

general, the higher the concrete resistivity, the lower the corrosion current. As for the case of corrosion currents, field measurements are adjusted to 70 F (21 C) utilizing an experimentally defined equation (3). For this study, it would have been desirable that the concrete resistivities were constant for all slabs with a given water cement ratio. However, previous studies have shown that when using 9-year old chloride contaminated slabs with varying degrees of corrosion damage, wide variations in resistivity at constant temperature can be expected. A valid rate of corrosion comparison must consider these non-rebar variations.

(4) 70 F (21C) Metal Consumed - This calculation is the amount of metal which would have been consumed during the test period if each concrete resistivity had constantly been at its 70 F (21C) adjusted value. It is well known (4) that each 1.0 amp-hr. of corrosion current consumes 1.04 g of iron or 1.22 grams of zinc. Total amp-hr. of current passed is calculated by multiplying the average corrosion current for each 2 successive readings by the hours between readings and accumulating a total.

A detailed listing of the data obtained during the study is presented in the Appendix. Figure 2 is a bar graph showing the average driving voltage of the corrosion macrocell in each slab. Figure 3 shows the average and range of corrosion currents obtained for each slab. The weighted average is used rather than simple arithmetic average because the time interval between data points was not a constant. Figure 4 shows the metal consumed.

Table 5 is a summary of the electrical half cell potential data collected during the study. A complete listing of the data is contained in the appendix. Potential data through July 10, 1981 included measurements on the top rebar mat from the top surface. Subsequent to that date, bottom rebar mat potentials were also obtained. The procedure used to measure potentials involved the uncoupling of the rebar mats, the grounding to the top mat and measurement from the top surface; and then the grounding to the bottom mat and the measurement of potentials from the bottom surface of the slab. In general, 3 constant measurement points on each surface were used. Total time required to complete the potential measurements was typically 2 to 3 minutes. As a result, a small amount of depolarization normally occurs during the measurement process if corrosin cells exist within the slabs. Testing with the mats coupled indicates the magnitude of the depolarization is typically in the range of 25 to 50 mV. Sample data taken within a 1-hour period with and without the mats coupled is given in the Appendix.

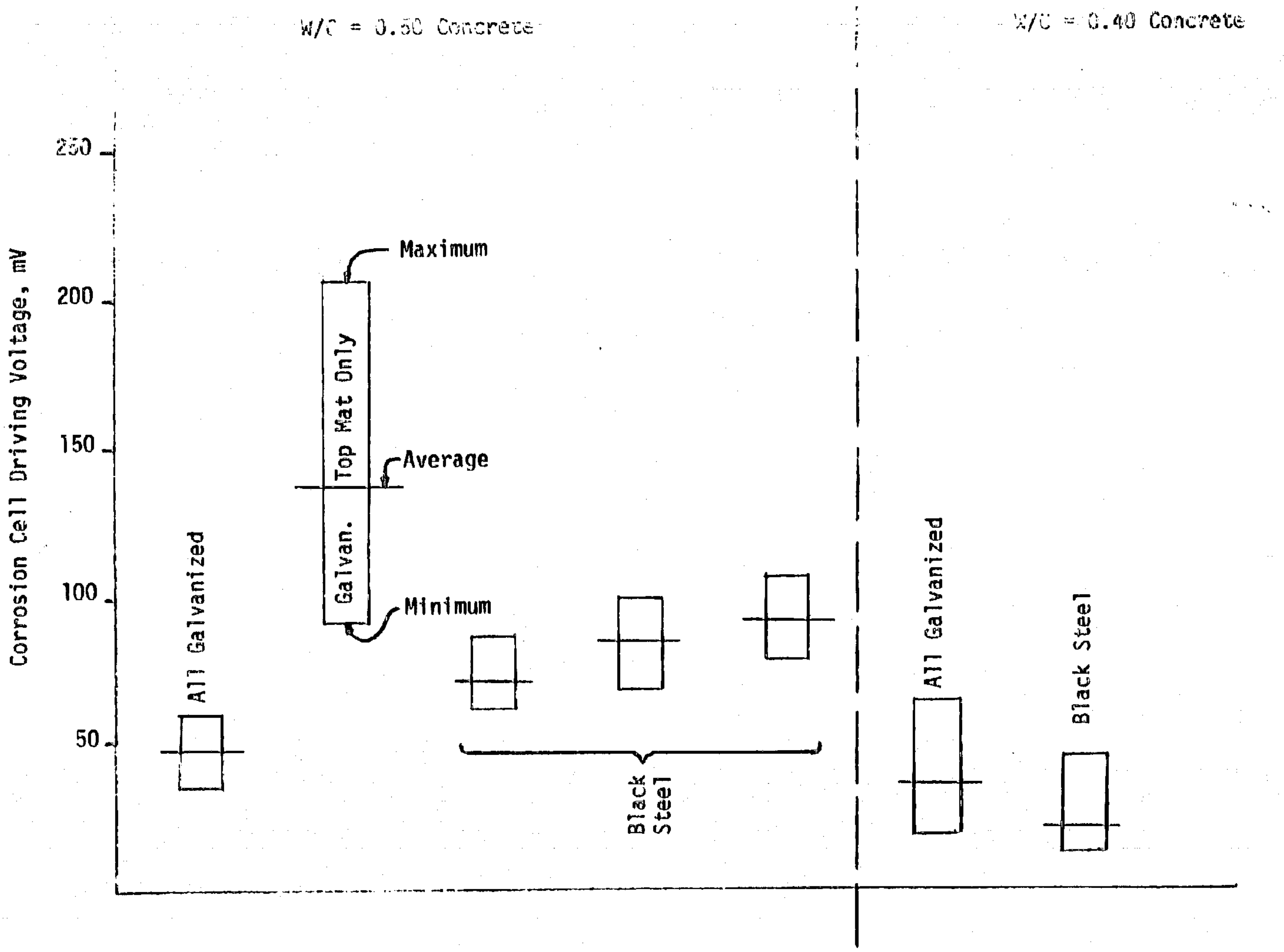
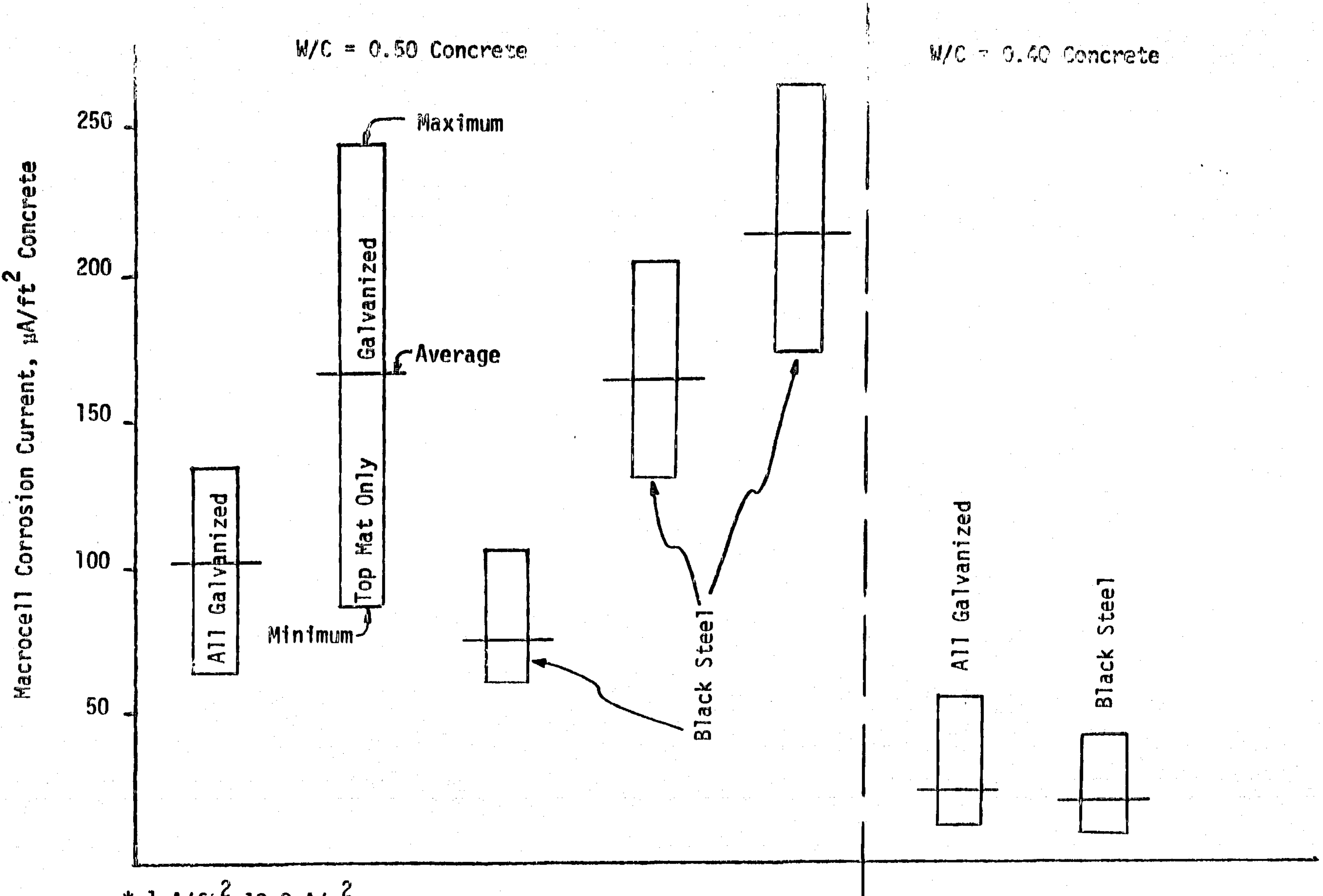
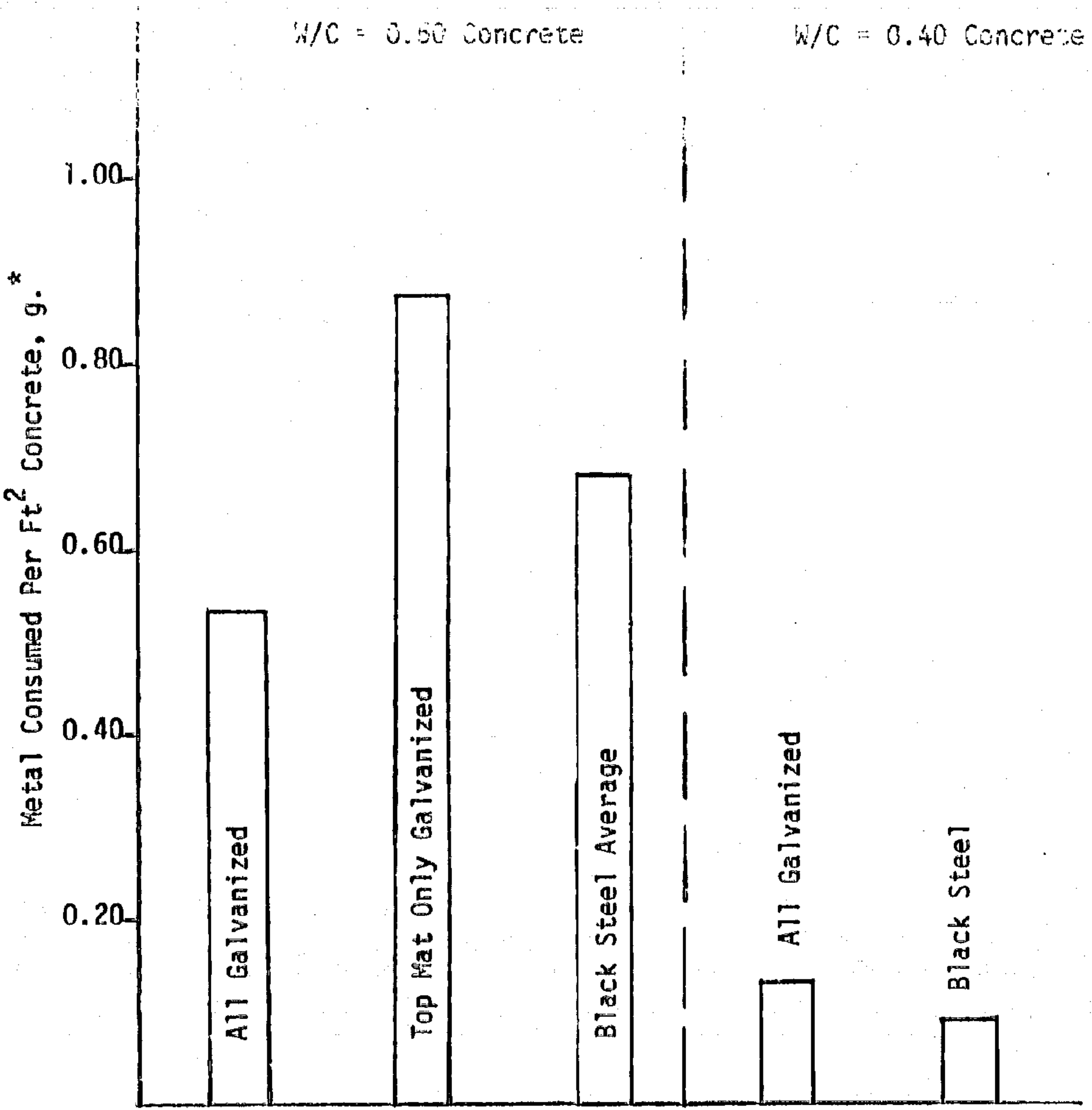


Figure 2, Corrosion Cell Voltage



* $1 \mu A/ft^2 = 10.8 \mu A/m^2$

Figure 3. Macrocell Corrosion Currents



* 1gm/ft^2 = 10.8gm/m^2

Figure 4. Metal Consumed

TABLE 5

Summary of Electrical Potential Data

		Electrical Potential, mV CSE			
Slab Number	Variable	Ave. Top Mat 4/20 thru 9/28	Ave. Top Mat 7/21 thru 9/28	Ave. Bottom Mat 7/21 thru 9/28	Average Top and Bottom Mat Difference, mV 7/21 thru 9/28
W/C = 0.50 Concrete - Salted					
54-81	All Galvan.	-621	-671	-385	-286
113-82	Top Mat Galvan.	-645	-707	-168	-539
90-112	Black Steel	-508	-519	-135	-384
99-15	Black Steel	-540	-549	-224	-325
21-105	Black Steel	-551	-574	-203	-371
W/C = 0.50 Concrete - No Salt					
77-38	Black Steel	-133	-120	-27	-93
W/C = 0.40 Concrete - Salted					
105-79	All Galvan.	-625	-687	-390	-297
9-39	Black Steel	-344	-400	-194	-206

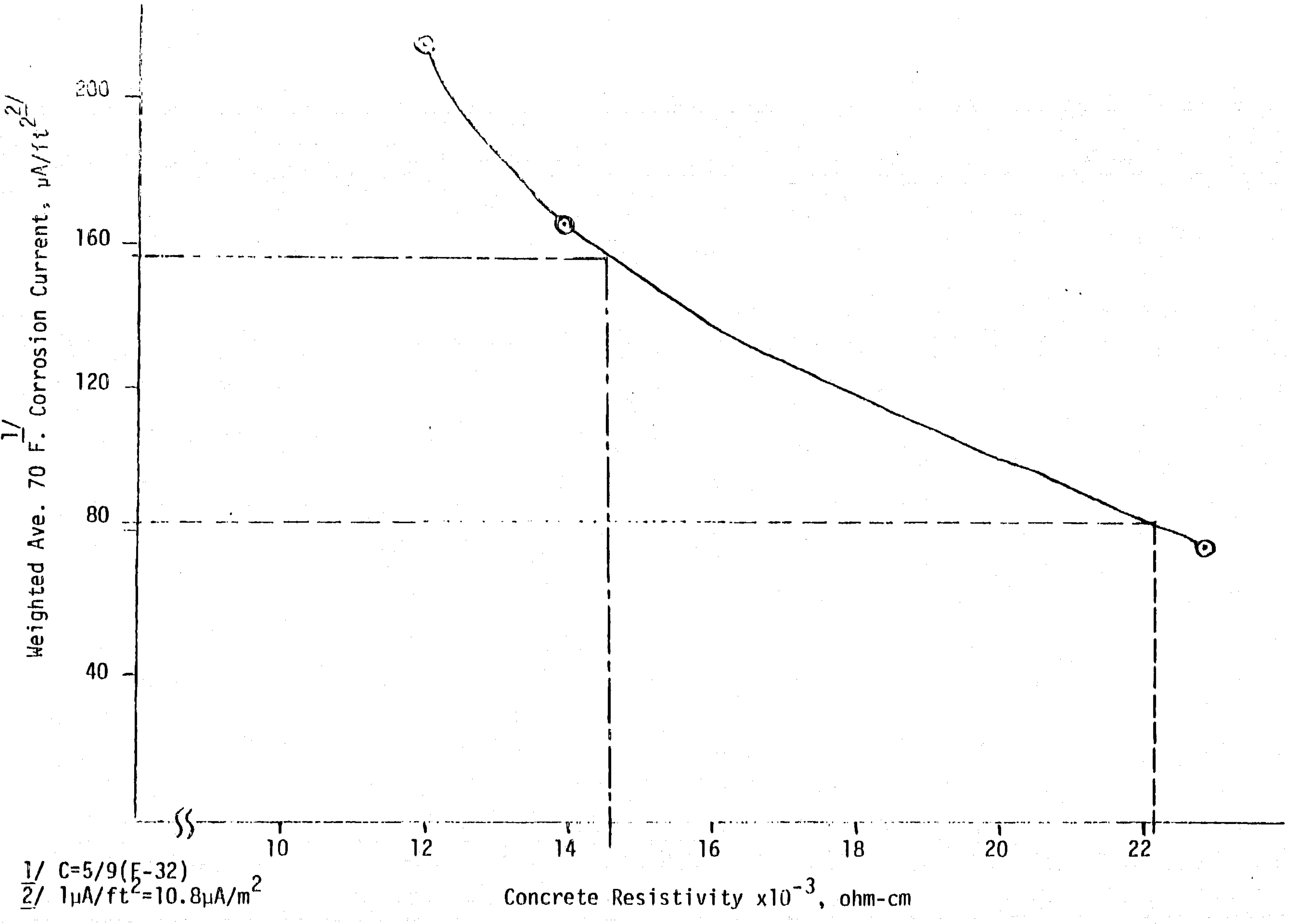
Open-circuit potentials taken by disconnecting the two rebar mats and making measurements within 3 minutes. Top-mat potentials were taken from the top surface with the positive lead attached to the top mat rebar, while bottom mat potentials were taken from the bottom surface with the postive lead attached to the bottom mat.

As expected, the data for the unsalted 0.50 water cement ratio slab show that no corrosion cell developed. Both the corrosion cell driving voltage and the corrosion current were zero in every instance. Top mat electrical potentials were typically in the range of -120mV CSE, a value indicative of passive steel. The potential difference between the rebar in the two mats was typically 100mV or less, another indicator that a corrosion macrocell did not exist.

Conversely, significant corrosion macrocells existed on all the chloride contaminated slabs regardless of whether or not they contained black steel, galvanized steel or a combination thereof. The electrical potential data show average top and bottom mat potential differences of over 200 mV for all these slabs. The largest difference (average = 539mV) occurred on the 0.50 water cement ratio slab with galvanized rebar in the top mat only, while the smallest (206mV) occurred on the black steel 0.40 water cement ratio slab. Galvanizing all the rebar in a slab caused both top and bottom mat potentials to be more negative than those typically seen on black steel slabs. Even so, large mat to mat differences existed within each of the galvanized slabs and thus macroscopic corosion occurred.

Examination of the corrosion current, metal consumption and cell driving voltage data (figures 2, 3, and 4) indicates that in general, galvanized reinforcing steel in chloride contaminated concrete corrodes in the same way and at about the same rate as black steel. Also, the data clearly show that black steel corrosion within a 0.40 water cement (w/c) ratio concrete is far less than that within a 0.50 w/c concrete. The corrosion current in the 0.40 w/c black steel slab was only 1/7th of the average value for the three 0.50 w/c slabs with black steel. One can therefore say the change in water cement ratio alone resulted in a decrease in corrosion rate of 86 percent.

Upon further examination of the data, some other differences in performance are clear. In general, for the 0.50 water-cement ratio concretes, the cell driving voltage data indicate that the worst case is the situation in which galvanized reinforcing steel in chloride-contaminated concrete is coupled with black steel in chloride-free concrete, while the best case is that in which all the rebar is galvanized. The corrosion current data do not completely reflect this in their present form because of the highly variable mat-to-mat resistances (i.e. different concrete resistivities). For example, the widely variable average corrosion currents for the w/c = 0.50 black steel slabs is obviously resistivity related (see table 4). Figure 5 shows a plot of concrete resistivity versus average



1/ C=5/9(F-32)
2/ 1μA/ft^2=10.8μA/m^2

Figure 5. Concrete Resistivity vs Corrosion Current

corrosion current for the salted 0.50 water cement ratio slabs with black steel. Using that plot, the corrosion current for any slab with a concrete resistivity in the range of 12,000 to 23,000 ohm-cm can be obtained. Such a procedure permits the determination of an average black steel corrosion current (and then metal consumed) at a concrete resistivity equal to that of each slab containing galvanized rebar. When this is done:

1. Black steel @22,140 ohm-cm
   Average corrosion current = 83 μA/ft^2 (893 μA/m^2)
   Metal consumed = 0.37 grams/ft^2 (3.98g/m^2)

2. Black steel @ 14,645 ohm-cm
   Average corrosion current = 155 μA/ft^2 (1668 μA/m^2)
   Metal consumed = 0.69 grams/ft^2 (7.42g/m^2)

Item one above is directly comparable to the findings on slab 113-82 containing a galvanized rebar top mat and a black steel bottom mat (average corrosion current = 166 μA/ft^2 (1786 μA/m^2) and metal consumed = 0.87 grams/ft^2 (9.36g/m^2). Thus, these data confirm that if only the top rebar mat is galvanized, the corrosion rate will be higher than if all black steel had been used. Such a procedure would double the corrosion current and increase the metal consumption rate by a factor of 2.4.

Item two above is directly comparable to the findings on slab 54-81 containing all galvanized rebar (average corrosion current = 102 μA/ft^2 (1098 μA/m^2) and metal consumed = 0.54 grams/ft^2 (5.81g/m^2)). A comparison indicates that galvanizing all the rebar in a 0.50 water cement ratio concrete is somewhat beneficial. Macrocell corrosion current was reduced by one third (34 percent) while metal consumption was reduced by about 22 percent.

For the 0.40 water-cement ratio slabs, somewhat different findings resulted. One slab contained all black steel, while the other contained all galvanized rebar. Both the average corrosion current data and the average driving voltage data indicate no benefit from galvanizing the rebar. In fact, the corrosion rate in the galvanized rebar slab averaged slightly higher than that for the black rebar slab, even though the concrete resistivity is higher in the galvanized rebar slab.

Summary

Over 9 years of outdoor exposure testing and 6 months of rate of corrosion measurements of galvanized and black reinforcing steel in slabs subjected to deicing salt indicates the following:

(1) Galvanized rebar in concrete containing chloride is subject to the same type of macroscopic corrosion as black steel.

(2) Both the long term exposure data and the rate of corrosion data indicate no benefit, and perhaps a slight detriment, when all the rebar is galvanized and a 0.40 water cement ratio concrete is used.

(3) Studies using 0.50 water-cement ratio concrete indicate that:

(a) The combination of galvanized rebar in chloride-contaminated concrete and black steel in chloride-free concrete (electrically coupled) is particularly bad. The rate of corrosion was more than twice as high for this situation than for the equal concrete in which all black reinforcing steel was used.

(b) Both the long-term exposure data and the rate of corrosion data indicate a benefit when all the rebar in a 0.50 water-cement-ratio concrete is galvanized. Significant corrosion-induced cracking has occurred on the black steel slabs with concrete of this water-cement ratio but not on the galvanized rebar slabs. Rate of corrosion data indicate about a 34 percent reduction in macrocell corrosion current and a 22 percent reduction in metal loss. This benefit is, however, far less than that which would be obtained by using black steel and 0.40 water-cement ratio concrete (average of 85 percent reduction in both corrosion current and metal loss).

References

1. Clear, K. C. and Hay, R. E., "Time-to-Corrosion of Reinforcing Steel in Concrete Slabs, Vol. 1: Effect of Mix Design and Construction Parameters," Federal Highway Administration, Report No. FHWA-RD-73-32, April 1973.

2. Clear, K. C., "Time-to-Corrosion of Reinforcing Steel in Concrete Slabs, Vol. 3: Performance After 830 Daily Salt Applications," Federal Highway Administration, Report No. FHWA-RD-76-70, April 1976.

3. FCP Annual Progress Report - Year Ending September 30, 1980, Project 4K, "Cost Effective Rigid Concrete Construction and Rehabilitation in Adverse Environments," Federal Highway Administration, 1980.

4. Myers, James R., "Fundamentals and Forms of Corrosion," Air Force Institute of Technology, October 1974.

Appendix
Corrosion Rate and Electrical Potential Data

A complete listing of the corrosion rate and electrical potential data collected during this study is contained in the tables which follow.

The first eight tables provide a tabulation of the corrosion rate data. For each test slab, the following data are provided.

a. Date the data were obtained.
b. Days under test in this substudy.
c. ΔV in mV. The measured driving voltage of the corrosion macrocell.
d. i_{70} in µA. The measured corrosion current adjusted to 70F (21C) using the temperature data listed and the formula listed in the text. Raw data (i.e. corrosion current at actual field temperature) could be calculated by solving the given formula for i_2.
e. R_{70} in ohms. The measured top mat to bottom mat 1000 cycle AC electrical resistance adjusted to 70F (21C). The lead wires which electrically connect the two rebar mats are uncoupled prior to this measurement. The formula utilized to adjust the measured resistance to 70 F (21C) is:

$$R_{70} = R_2 \, e^{2883\left(\frac{1}{T_1} - \frac{1}{T_2}\right)}$$

where:

R_2 = measured resistance at field temperature.
T_1 = 70 F (21C) expressed in degrees Kelvin (294.1K)
T_2 = average field tempeature in degrees Kelvin

The actual measured resistance can be calculated by solving the above equation for R_2. Also, the concrete resistivity can be defined by multiplying the resistance values by experimentally defined cell constants (660 for the 20 ft^2 ($1.9m^2$) slabs and 376 for the 10 ft^2 ($0.9m^2$) slabs). These constants were defined by placing duplicates of the entire rebar system in the slabs (in the exact configuration used) in solutions of known resistivity and then measuring the resistance.

f. Approximate actual temperature, C. The approximate temperature of the concrete between the two mats of reinforcing steel. Since all slabs were stored at a common location at the test yard, a single set of temperature measurements on a control slab was assumed to be representative of all the slabs. Previous efforts in which thermocouples in each slab were repeatedly measured, support the adequacy of this approach.

g. Cumulative amp-hrs of corrosion. This is a measure of the area under a plot of i_{70} in amps and time in hours in which all data points are connected by straight lines. Mathmatically, it is calculated by multiplying the average 70 F (21C) corrosion current for each two successive readings by the time between the readings, and accumulating a total. For the initial calculation (that between zero time and data point 1) the corrosion current is assumed to be constant at the data point, one measured value. When more than one data point were available for a single day, that day's data were averaged prior to the cumulative amp-hrs calculation.

   The actual average corrosion current (called the weighted average) during the test period can be calculated by dividing the total cumulative amp-hours by the test time in hours and multiplying by 1 million to convert to micro-amps. This value is more representative than the arithmetic average of the measured values since the time between measurements was not constant.

h. 70 F. (21 C.) metal consumed, grams. These data are obtained by multiplying cumulative amp-hours by 1.04 grams/amp-hour when iron corrosion is occurring and 1.22 grams/amp-hour when zinc corrosion is assumed to be the primary metal loss reaction.

Following the tabulation of the data for each slab, the data are reduced to averages per square foot of concrete surface to allow easier comparison of the one-half slab to the full slabs. Such a procedure can be used in this instance because the reinforcing steel (top mat and bottom mat) in the half-slab is approximately one half that in the full slabs.

The electrical potential data obtained during the study are presented in the tables following the corrosion rate data and are discussed in the body of this report.

TABLE 6.

Data On Slab No: 54-81; 10ft^2(0.9m^2) Slab
Variable: W/C = 0.50, Both Mats Galvanized.

Date	Days	ΔV mV	i_{70} μA	R_{70} Ω	Approx. Actual Temp °C	Cumul. Amp-hrs	70°F Metal Consumed grams
4/2/81	0	-	-	-	-	0	0
4/7	5	36	760	-	20.3	0.97	0.118
4/7	5	38	859	34.8	16.7		
4/8	6	40	859	35.2	20.4	0.117	0.143
4/13	11	43	828	41.6	13.1	0.219	0.267
4/15	13	54	1027	-	21	0.263	0.321
4/20	18	46	869	38.6	12.2	0.376	0.459
4/20	18	51	1098	-	22.2		
4/21	19	46	1060	34.0	5.8	0.401	0.489
4/22	20	45	929	37.0	6.7	0.425	0.518
4/27	25	45	1143	33.8	17.1	0.550	0.670
4/28	26	51	1100	37.6	30.5	0.576	0.703
4/29	27	47	753	48.5	26.5	0.598	0.730
5/4	32	52	1179	35.9	15.3	0.713	0.870
5/7	35	49	1132	34.4	9.2	0.796	0.971
5/12	40	56	1290	35.8	20.6	0.935	1.14
5/19	47	45	973	39.2	10.7	1.118	1.36
5/29	57	63	1354	36.6	27.5	1.397	1.70
6/11	70	62	1206	40.2	21.2	1.796	2.19
6/23	82	-	-	-	21.6	-	-
6/29	88	-	-	-	20.3	-	-
7/1	90	59	1092	42.8	29.6	2.348	2.86
7/10	99	55	1066	41.8	29.1	2.581	3.15
7/21	110	42	736	45.2	25.1	2.819	3.44
7/27	116	54	1080	40.4	25.3	2.950	3.60
8/7	127	57	1172	38.0	25.4	3.247	3.96
8/20	140	48	1153	34.4	21.3	3.610	4.40
9/3	154	41	749	43.6	23.9	3.930	4.79
9/9	160	38	703	40.2	14.4	4.035	4.92
9/14	165	43	871	39.6	28.5	4.129	5.04
9/17	168	43	829	-	20.7	4.190	5.11
9/23	174	36	641	43.2	12.7	4.295	5.24
9/28	179	40	737	40.3	16.5	4.378	5.34
AVE		47.5	971	38.95			
Weighted Ave.			1025				

Ave. i_{70}, μA/ft^2(μA/m^2) of Concrete Surface 97.1(1044.8)

Weighted Ave i_{70}, μA/ft^2 (μA/m^2) of Concrete Surface 102.5(1102.9)

Ave. Metal Consumed, g/ft^2(g/m^2) of Concrete Surface 0.537(5.779)

TABLE 7.

Data On Slab No: 113-82; 20 ft^2(1.9m^2) Slab
Variable: w/c=0.50, Galvan. Top, Black Steel Bottom

Date	Days	ΔV mV	i_{70} μA	R_{70} Ω	Approx. Actual Temp °C	Cumul. Amp-hrs	70°F Metal Consumed grams
4/2/81	0	-	-	-	-	0	0
4/7	5	91	1756	-	20.3	0.227	0.28
4/7	5	92	2030	30.8	16.7		
4/8	6	87	1893	30.7	20.4	0.273	0.34
4/13	11	95	1748	34.7	13.1	0.491	0.60
4/15	13	112	1810	-	21	0.576	0.71
4/20	18	105	2039	33.8	12.2	0.830	1.02
4/20	18	125	2792	-	22.2		
4/21	19	91	1983	33.3	5.8	0.883	1.08
4/22	20	94	1775	35.7	6.7	0.928	1.13
4/27	25	115	2504	31.9	17.1	1.185	1.45
4/28	26	146	3057	34.0	30.5	1.251	1.53
4/29	27	120	1897	43.4	26.5	1.311	1.60
5/4	32	122	2681	33.6	15.3	1.585	1.93
5/7	35	122	2582	32.9	9.2	1.775	2.17
5/12	40	146	3254	31.6	20.6	2.125	2.59
5/19	47	124	2333	36.0	10.7	2.594	3.16
5/29	57	179	4540	36.3	27.5	3.419	4.17
6/11	70	194	3607	35.6	21.2	4.690	5.72
6/23	82	165	3486	36.3	21.6	5.711	6.97
6/29	88	149	2949	39.7	20.3	6.175	7.53
7/1	90	183	4201	35.3	29.6	6.346	7.74
7/10	99	206	4896	33.8	29.1	7.329	8.94
7/21	110	151	3469	34.6	25.1	8.433	10.29
7/27	116	185	4945	30.6	25.3	9.039	11.03
8/7	127	189	2292	28.0	25.4	9.994	12.19
8/20	140	-	2923	27.3	21.3	10.808	13.19
9/3	154	152	3962	33.4	23.9	11.964	14.60
9/9	160	128	3515	32.2	14.4	12.503	15.25
9/14	165	168	4591	31.2	28.5	12.989	15.85
9/17	168	153	4147	31.0	20.7	13.304	16.23
9/23	174	126	3085	34.6	12.7	13.824	16.87
9/28	179	143	3803	30.7	16.5	14.238	17.37
AVE		137.4	3017	33.55			
Weighted Ave.			3314				

Ave. i_{70}, μA/ft^2(μA/m^2) of Concrete Surface 150.9(1623.7)

Weighted Ave. i_{70}, μA/ft^2 (μA/m^2) of Concrete Surface. 165.7(1782.9)

Ave. Metal Consumed, g/ft^2(g/m^2) of Concrete Surface 0.869(9.350)

TABLE 8.

Data On Slab No: 90-112; 20 $ft^2 (1.9m^2)$ Slab
Variable: w/c=0.50 Black Steel

Date	Days	ΔV mV	i_{70} μA	R_{70} Ω	Approx. Actual Temp °C	Cumul. Amp-hrs	70°F Metal Consumed grams
4/2/81	0	-	-	-	-	0	0
4/7	5	72	1624	31.2	20.3	0.207	0.22
4/7	5	75	1818	-	16.7		
4/8	6	74	1729	31.2	20.4	0.248	0.26
4/13	11	74	1669	33.4	13.1	0.452	0.47
4/15	13	79	1729	-	21	0.533	0.55
4/20	18	73	1616	33.9	12.2	0.740	0.77
4/20	18	77	1810	-	22.2		
4/21	19	71	1402	36.1	5.8	0.777	0.81
4/22	20	86	2140	35.0	6.7	0.820	0.85
4/27	25	75	1658	32.8	17.1	1.048	1.09
4/28	26	76	1654	34.4	30.5	1.087	1.13
4/29	27	76	1240	45.0	26.5	1.122	1.17
5/4	32	76	1536	36.4	15.3	1.289	1.34
5/7	35	68	1389	36.2	9.2	1.394	1.45
5/12	40	77	1688	33.0	20.6	1.578	1.64
5/19	47	71	1417	35.8	10.7	1.838	1.91
5/29	57	75	1638	32.3	27.5	2.205	2.29
6/11	70	75	1654	32.8	21.2	2.719	2.83
6/23	82	70	1477	34.1	21.6	3.170	3.30
6/29	88	64	1418	32.3	20.3	3.378	3.51
7/1	90	67	1458	34.0	29.6	3.447	3.58
7/10	99	72	1600	33.8	29.1	3.777	3.93
7/21	110	61	1332	34.8	25.1	4.164	4.33
7/27	116	70	1567	33.7	25.3	4.373	4.55
8/7	127	69	1484	34.1	25.4	4.776	4.97
8/20	140	63	1302	36.2	21.3	5.211	5.42
9/3	154	63	1369	36.3	23.9	5.660	5.89
9/9	160	62	1419	33.9	14.4	5.861	6.10
9/14	165	66	1578	31.6	28.5	6.041	6.28
9/17	168	73	1582	35.3	20.7	6.155	6.40
9/23	174	68	1376	33.6	12.7	6.368	6.62
9/28	179	65	1358	35.9	16.5	6.532	6.79
AVE		71.3	1554	34.62			
Weighted Ave.			1520				

Ave. i_{70}, $\mu A/ft^2 (\mu A/m^2)$ of Concrete Surface 77.7(936.1)

Weighted Ave. i_{70}, $\mu A/ft^2 (\mu A/m^2)$ of Concrete Surface 76.0 (0.340)

Ave. Metal Consumed.

TABLE 9.

Data On Slab No: 99-15, 20ft^2 $(1.9m^2)$ Slab
Variable: Black Steel, w/c=0.50

Date	Days	ΔV mV	i_{70} μA	R_{70} Ω	Approx. Actual Temp C.	Cumul. Amp-hrs	70°F Metal Consumed grams
4/2/81	0	-	-	-	-	0	0
4/7	5	91	3921	-	20.3	0.457	0.48
4/7	5	88	3690	20.2	16.7		
4/8	6	90	3683	20.2	20.4	0.547	0.57
4/13	11	100	4061	21.0	13.1	1.011	1.05
4/15	13	96	3772	-	21	1.199	1.25
4/20	18	96	3761	21.1	12.2	1.651	1.72
4/20	18	98	4082	-	22.2		
4/21	19	89	3266	22.9	5.8	1.737	1.81
4/22	20	86	3252	21.9	6.7	1.816	1.89
4/27	25	88	3453	21.2	17.1	2.218	2.31
4/28	26	90	3411	21.7	30.5	2.300	2.39
4/29	27	91	2697	27.8	26.5	2.374	2.47
5/4	32	89	3156	23.5	15.3	2.725	2.83
5/7	35	86	3126	22.9	9.2	2.951	3.07
5/12	40	96	3956	20.4	20.6	3.376	3.51
5/19	47	89	3463	21.5	10.7	4.000	4.16
5/29	57	91	3624	20.0	27.5	4.850	5.04
6/11	70	86	3537	20.1	21.2	5.967	6.21
6/23	82	81	3349	20.1	21.6	6.959	7.24
6/29	88	73	2826	21.0	20.3	7.404	7.70
7/1	90	81	3390	19.8	29.6	7.553	7.86
7/10	99	79	3221	19.8	29.1	8.267	8.60
7/21	110	71	2777	20.6	25.1	9.059	9.42
7/27	116	87	3448	20.4	25.3	9.507	9.89
8/7	127	83	3411	20.1	25.4	10.412	10.83
8/20	140	69	2635	21.1	21.3	11.355	11.81
9/3	154	71	2858	20.9	23.9	12.278	12.77
9/9	160	70	3000	19.6	14.4	12.700	13.21
9/14	165	72	3116	18.8	28.5	13.067	13.59
9/17	168	84	3488	20.1	20.7	13.305	13.84
9/23	174	80	3072	21.5	12.7	13.777	14.33
9/28	179	70	2773	21.1	16.5	14.128	14.69
AVE		84.7	3352	21.08			
Weighted Ave.			3289				

Ave. i_{70}, $\mu A/ft^2 (\mu A/m^2$ of Concrete Surface 167.6(1803.4)

Weighted Ave. i_{70}, $\mu A/ft^2 (\mu A/m^2)$ of Concrete Surface 164.4(1768.9)

Ave. Metal Consumed. $g/ft^2 (g/m^2)$ of Concrete Surface 0.734(7.998)

TABLE 10.

Data On Slab No: 21-105; 20 Ft^2(1.9m^2) Slab
Variable: w/c=0.50, Black Steel

Date	Days	ΔV mV	i_{70} μA	R_{70} Ω	Approx. Actual Temp °C	Cumul. Amp-hrs	70°F Metal Consumed grams
4/2/81	0	-	-	-	-	0	0
4/7	5	99	4889	-	20.3	0.575	0.60
4/7	5	94	4687	16.9	16.7		
4/8	6	95	4737	16.9	20.4	0.689	0.72
4/13	11	106	5296	16.9	13.1	1.290	1.34
4/15	13	107	5145	-	21	1.540	1.60
4/20	18	98	4780	17.0	12.2	2.149	2.23
4/20	18	104	5199	-	22.2		
4/21	19	91	4480	17.2	5.8	2.262	2.35
4/22	20	91	4290	17.4	6.7	2.367	2.46
4/27	25	94	4505	17.1	17.1	2.895	3.01
4/28	26	100	4511	18.1	30.5	3.003	3.12
4/29	27	95	3501	22.8	26.5	3.099	3.23
5/4	32	99	4643	17.9	15.3	3.588	3.73
5/7	35	90	4183	17.8	9.2	3.906	4.06
5/12	40	102	5003	17.2	20.6	4.457	4.64
5/19	47	91	4308	17.7	10.7	5.239	5.45
5/29	57	95	4630	17.1	27.5	6.312	6.56
6/11	70	97	4743	17.1	21.2	7.774	8.08
6/23	82	90	4436	17.2	21.6	9.096	9.46
6/29	88	81	3710	18.0	20.3	9.682	10.07
7/1	90	91	4247	18.0	29.6	9.873	10.27
7/10	99	93	4273	17.5	29.1	10.793	11.22
7/21	110	79	3513	18.6	25.1	11.821	12.29
7/27	116	95	4388	19.1	25.3	12.390	12.89
8/7	127	95	4279	18.4	25.4	13.534	14.08
8/20	140	78	3623	18.3	21.3	14.767	15.36
9/3	154	85	3638	19.4	23.9	15.995	16.63
9/9	160	86	3753	20.2	14.4	16.531	17.19
9/14	165	81	3509	19.2	28.5	16.966	17.64
9/17	168	100	4532		20.7	17.256	17.95
9/23	174	88	3887	18.9	12.7	17.862	18.58
9/28	179	90	3903	19.1	16.5	18.329	19.06
AVE		93.1	4352	18.10			
Weighted Ave.			4291				

Ave. i_{70}, μA/ft^2(μA/m^2) of Concrete Surface 217.6(2341.4)

Weighted Ave. i_{70}, μA/ft^2 (μA/m^2) of Concrete Surface 214.6(2309.1)

Ave. Metal Consumed, g/ft^2 (g/m^2) of Concrete Surface 0.953(10.254)

TABLE [illegible].

Data On Slab No: 105-79; 20 Ft^2(1.9m^2) Slab
Variable: w/c=0.40 Both mats galvan.

Date	Days	ΔV mV	i_{70} μA	R_{70} Ω	Approx. Actual Temp °C	Cumul. Amp-hrs	70°F Metal Consumed grams
4/2/81	0	-	-	-	-	0	0
4/7	5	39	576	-	20.3	0.081	0.10
4/7	5	52	766	55.9	16.7		
4/8	6	34	552	51.7	20.4	0.096	0.12
4/13	11	64	1130	47.9	13.1	0.197	0.24
4/15	13	64	1076	-	21	0.250	0.30
4/20	18	29	502	52.0	12.2	0.349	0.43
4/20	18	36	655	-	22.2		
4/21	19	40	564	50.8	5.8	0.363	0.44
4/22	20	31	465	53.6	6.7	0.375	0.46
4/27	25	31	572	45.3	17.1	0.438	0.53
4/28	26	31	554	45.1	30.5	0.451	0.55
4/29	27	26	335	62.4	26.5	0.462	0.56
5/4	32	32	536	49.6	15.3	0.514	0.63
5/7	35	24	378	49.4	9.2	0.547	0.67
5/12	40	26	437	46.6	20.6	0.596	0.73
5/19	47	19	272	53.5	10.7	0.655	0.80
5/29	57	26	446	46.1	27.5	0.742	0.90
6/11	70	30	399	58.2	21.2	0.873	1.07
6/23	82	29	365	60.7	21.6	0.983	1.20
6/29	88	27	298	65.5	20.3	1.031	1.26
7/1	90	37	522	56.9	29.6	1.051	1.28
7/10	99	38	502	58.4	29.1	1.161	1.42
7/21	110	33	386	63.0	25.1	1.279	1.56
7/27	116	55	714	57.8	25.3	1.358	1.66
8/7	127	59	833	53.0	25.4	1.562	1.91
8/20	140	38	626	49.1	21.3	1.790	2.18
9/3	154	35	420	62.4	23.9	1.965	2.40
9/9	160	31	364	62.5	14.4	2.022	2.47
9/14	165	34	495	53.0	28.5	2.073	2.53
9/17	168	37	466	60.5	20.7	2.108	2.57
9/23	174	35	361	71.6	12.7	2.167	2.64
9/28	179	32	375	63.7	16.5	2.211	2.70
AVE		36.1	529	54.84			
Weighted Ave.			503				

Ave. i_{70}, μA/ft^2(μA/m^2) of Concrete Surface 26.5(285.1)

Weighted Ave. i_{70}, μA/ft^2 (μA/m^2) of Concrete Surface 25.2(271.2)

Ave. Metal Consumed, g/ft^2 (g/m^2) of Concrete Surface 0.135(1.453)

TABLE 12.

Data On Slab No: 9-39; 20 Ft^2 (1.9m^2) Slab
Variable: w/c=0.40 Black Steel

Date	Days	ΔV mV	i_{70} μA	R_{70} Ω	Approx. Actual Temp °C	Cumul. Amp-hrs	70°F Metal Consumed grams
4/2/81	0	-	-	-	-	0	0
4/7	5	-	-	-	20.3	-	-
4/7	5	-	-	-	16.7	-	-
4/8	6	-	-	-	20.4	-	-
4/13	11	16	276	46.3	13.1	0.073	0.08
4/15	13	14	234	-	21	0.085	0.09
4/20	18	16	253	45.2	12.2	0.115	0.12
4/20	18	15	270	-	22.2		
4/21	19	13	205	39.7	5.8	0.121	0.13
4/22	20	13	199	43.2	6.7	0.125	0.13
4/27	25	13	252	37.7	17.1	0.153	0.16
4/28	26	13	273	40.4	30.5	0.159	0.17
4/29	27	13	201	53.6	26.5	0.164	0.17
5/4	32	15	280	40.0	15.3	0.193	0.20
5/7	35	14	272	39.1	9.2	0.213	0.22
5/12	40	16	305	40.2	20.6	0.248	0.26
5/19	47	18	286	46.8	10.7	0.298	0.31
5/29	57	19	373	40.1	27.5	0.377	0.39
6/11	70	21	379	45.5	21.2	0.496	0.51
6/23	82	21	365	46.3	21.6	0.601	0.63
6/29	88	20	339	50.0	20.3	0.652	0.68
7/1	90	22	372	44.1	29.6	0.669	0.70
7/10	99	22	409	44.5	29.1	0.753	0.78
7/21	110	23	394	47.1	25.1	0.859	0.89
7/27	116	28	522	43.2	25.3	0.925	0.96
8/7	127	29	443	39.5	25.4	1.052	1.09
8/20	140	32	726	35.0	21.3	1.235	1.28
9/3	154	33	548	47.3	23.9	1.449	1.51
9/9	160	33	552	47.4	14.4	1.528	1.59
9/14	165	34	691	40.0	28.5	1.603	1.67
9/17	168	36	649	44.4	20.7	1.651	1.72
9/23	174	37	574	51.7	12.7	1.739	1.81
9/28	179	46	866	41.3	16.5	1.825	1.90
AVE		22.2	397	43.69			

Weighted Ave.	425
Ave. i_{70}, μA/ft^2 (μA/m^2) of Concrete Surface	19.8 (213.0)
Weighted Ave. i_{70}, μA/ft^2 (μA/m^2) of Concrete Surface.	21.3 (292.2)
Ave. Metal Consumed, g/ft^2 (g/m^2) of Concrete Surface	0.095 (1.022)

TABLE 13.

Data On Slab No: 77-38; 20 ft^2 (1.9m^2) Slab
Variable: w/c=0.50 Black Steel-Salt Free

Date	ΔV	i_{70}	R_{70}	Approx. Actual Temp °C	Cumul. Amp-hrs	70°F Metal Consumed
3/23/81	0	0	35.3	6	0	0
4/15	0	0	31.2	22	0	0
4/29	0	0	38.2	25	0	0
5/18	0	0	33.7	16	0	0
6/16	0	0	29.7	27	0	0
6/23	0	0	36.1	33	0	0
7/10	0	0	35.1	30	0	0
7/28	0	0	39.7	25	0	0
AVE	0	0	34.88		0	0

TABLE 14.

Potentials for SLAB No. 54-81

Variable: w/c=0.60 All Galvanized

Date	Top Mat Potentials 1	Top Mat Potentials 2	Top Mat Potentials 3	Top Mat Potentials AVE	Bottom Mat Potentials 1	Bottom Mat Potentials 2	Bottom Mat Potentials 3	Bottom Mat Potentials AVE	Ave. Potential Diff.
4/20	-574	-490	-	-532	-	-	-	-	-
4/21	-531	-488	-	-510	-	-	-	-	-
4/22	-548	-490	-	-519	-	-	-	-	-
4/27	-598	-559	-	-579	-	-	-	-	-
4/28	-655	-579	-	-617	-	-	-	-	-
4/29	-577	-522	-	-550	-	-	-	-	-
5/7	-563	-540	-	-552	-	-	-	-	-
5/12	-592	-594	-	-593	-	-	-	-	-
5/19	-562	-518	-	-540	-	-	-	-	-
5/29	-702	-660	-	-681	-	-	-	-	-
5/11	-650	-690	-	-670	-	-	-	-	-
6/23	-658	-683	-	-671	-	-	-	-	-
6/29	-608	-672	-	-640	-	-	-	-	-
7/1	-606	-704	-	-655	-	-	-	-	-
7/10	-627	-674	-	-651	-	-	-	-	-
7/21	-597	-641	-	-619	-317	-359	-	-338	-281
7/27	-700	-622	-	-661	-470	-402	-	-436	-225
8/7	-747	-656	-	-701	-428	-375	-	-402	-299
8/20	-753	-603	-	-678	-384	-344	-	-364	-314
9/3	-676	-642	-	-659	-350	-398	-	-374	-285
9/14	-658	-709	-	-683	-384	-454	-	-419	-264
9/28	-765	-633	-	-699	-400	-327	-	-364	-335
AVERAGE OVERALL				-621					
AVERAGE (7/21 thru 9/28)				-671				-385	-286

Note: All potentials are mV to the copper sulfate electrode. The positive meter lead was connected to the reinforcing steel.

Measurements taken after uncoupling mats (within 3 minutes).

TABLE 15.

Potentials for SLAB No. 113-82

VARIABLE: w/c = 0.50; Top Mat Galvanized

Date	Top Mat Potentials 1	Top Mat Potentials 2	Top Mat Potentials 3	Top Mat Potentials Ave	Bottom Mat Potentials 1	Bottom Mat Potentials 2	Bottom Mat Potentials 3	Bottom Mat Potentials Ave	Ave. Potent Diff.
4/20	-554	-540	-502	-532	-	-	-	-	-
4/21	-535	-510	-484	-510	-	-	-	-	-
4/22	-504	-481	-436	-474	-	-	-	-	-
4/28	-645	-639	-566	-617	-	-	-	-	-
4/29	-634	-630	-577	-614	-	-	-	-	-
5/7	-571	-608	-574	-584	-	-	-	-	-
5/12	-616	-660	-602	-626	-	-	-	-	-
5/19	-631	-647	-588	-622	-	-	-	-	-
5/29	-681	-758	-648	-696	-	-	-	-	-
6/11	-698	-777	-663	-713	-	-	-	-	-
6/23	-658	-685	-611	-651	-	-	-	-	-
6/29	-544	-620	-625	-596	-	-	-	-	-
7/1	-688	-722	-670	-693	-	-	-	-	-
7/10	-721	-748	-693	-721	-	-	-	-	-
7/21	-659	-653	-616	-643	-212	-218	-212	-214	-429
7/27	-756	-773	-721	-750	-176	-191	-182	-183	-567
8/7	-734	-774	-725	-744	-172	-201	-142	-172	-572
9/3	-683	-666	-655	-668	-136	-196	-166	-166	-502
9/14	-718	-741	-739	-733	-147	-109	-128	-128	-605
9/28	-692	-734	-688	-705	-149	- 99	-182	-143	-562
AVERAGE				-645					
AVE. 7/21 thru 9/28				-707				-168	-539

Note: All potentials are mV to the copper sulfate electrode. The positive meter lead was connected to the reinforcing steel.

Measurements taken after uncoupling mats (within 3 minutes).

TABLE 16.

Potentials for SLAB No. 90-112

VARIABLE: Black Steel w/c = 0.50

Date	Top Mat Potentials 1	2	3	Ave	Bottom Mat Potentials 1	2	3	Ave	Ave. Potential Diff.
4/20	-425	-506	-560	-497	-	-	-	-	-
4/21	-535	-513	-426	-491	-	-	-	-	-
4/22	-401	-480	-547	-476	-	-	-	-	-
4/27	-463	-535	-585	-528	-	-	-	-	-
4/28	-589	-437	-539	-522	-	-	-	-	-
4/29	-426	-507	-577	-503	-	-	-	-	-
5/7	-391	-487	-568	-482	-	-	-	-	-
5/12	-595	-567	-480	-547	-	-	-	-	-
5/19	-571	-522	-462	-518	-	-	-	-	-
5/29	-581	-538	-469	-529	-	-	-	-	-
6/11	-573	-503	-459	-512	-	-	-	-	-
6/23	-545	-508	-458	-504	-	-	-	-	-
6/29	-389	-514	-496	-466	-	-	-	-	-
7/1	-436	-492	-520	-483	-	-	-	-	-
7/10	-513	-414	-503	-477	-	-	-	-	-
7/21	-527	-494	-451	-491	-160	-54	-107	-107	-384
7/27	-473	-515	-582	-523	-185	-112	-199	-165	-358
8/7	-543	-528	-445	-505	-208	-103	-158	-156	-349
8/20	-553	-500	-468	-507	-163	- 63	-138	-121	-386
9/3	-528	-488	-452	-489	-191	- 92	-150	-144	-345
9/14	-490	-512	-578	-527	-142	- 84	-171	-132	-395
9/28	-551	-600	-632	-594	-126	- 55	-180	-120	-474
AVERAGE				-508					
AVE. 7/21 thru 9/28				-519				-135	-384

Note: All potentials are mV to the copper sulfate electrode. The positive meter lead was connected to the reinforcing steel.

Measurements taken after uncoupling mats (within 3 minutes).

TABLE 17.

Potentials for SLAB No. 99-15

VARIABLE: Black Steel, w/c = 0.50

Date	Top Mat Potentials 1	2	3	Ave	Bottom Mat Potentials 1	2	3	Ave	Ave. Potential Diff.
4/20	-472	-595	-552	-540	-	-	-	-	-
4/21	-500	-558	-419	-492	-	-	-	-	-
4/22	-457	-566	-535	-519	-	-	-	-	-
4/27	-560	-612	-500	-557	-	-	-	-	-
4/28	-595	-582	-493	-557	-	-	-	-	-
4/29	-566	-587	-479	-544	-	-	-	-	-
5/7	-528	-439	-558	-508	-	-	-	-	-
5/12	-561	-623	-488	-557	-	-	-	-	-
5/19	-534	-593	-469	-532	-	-	-	-	-
5/29	-571	-616	-490	-559	-	-	-	-	-
6/11	-558	-577	-476	-537	-	-	-	-	-
6/23	-564	-598	-490	-551	-	-	-	-	-
6/29	-444	-590	-540	-525	-	-	-	-	-
7/1	-473	-584	-567	-541	-	-	-	-	-
7/10	-527	-554	-475	-519	-	-	-	-	-
7/21	-470	-600	-561	-544	-188	-188	-235	-204	-340
7/27	-590	-596	-506	-564	-287	-232	-216	-245	-319
8/7	-582	-597	-486	-555	-376	-329	-316	-340	-215
8/20	-542	-605	-490	-546	-225	-164	-166	-185	-361
9/3	-544	-575	-490	-536	-197	-215	-224	-212	-324
9/14	-503	-609	-518	-543	-188	-197	-234	-206	-337
9/28	-509	-614	-541	-555	-151	-163	-221	-178	-377
AVERAGE				-540					
AVE. 7/21 thru 9/28				-549				-224	-325

Note: All potentials are mV to the copper sulfate electrode. The positive meter lead was connected to the reinforcing steel.

Measurements taken after uncoupling mats (within 3 minutes).

TABLE 18.

Potentials for SLAB No. 21-105

VARIABLE: Black Steel, w/c = 0.50

Date	Top Mat Potentials 1	2	3	Ave	Bottom Mat Potentials 1	2	3	Ave	Ave. Potential Diff.
4/20	-535	-590	-578	-568	-	-	-	-	-
4/21	-462	-500	-535	-499	-	-	-	-	-
4/22	-508	-538	-527	-524	-	-	-	-	-
4/27	-534	-566	-558	-553	-	-	-	-	-
4/28	-536	-592	-567	-565	-	-	-	-	-
4/29	-536	-523	-435	-498	-	-	-	-	-
5/7	-494	-532	-505	-510	-	-	-	-	-
5/12	-553	-600	-598	-584	-	-	-	-	-
5/19	-553	-568	-560	-560	-	-	-	-	-
5/29	-512	-560	-574	-549	-	-	-	-	-
6/11	-525	-561	-560	-549	-	-	-	-	-
6/23	-532	-538	-559	-543	-	-	-	-	-
6/29	-502	-531	-535	-523	-	-	-	-	-
7/1	-520	-562	-550	-544	-	-	-	-	-
7/10	-519	-550	-556′	-542	-	-	-	-	-
7/21	-512	-527	-549	-529	-209	-200	-213	-207	-322
7/27	-564	-580	-591	-578	-192	-220	-269	-227	-351
8/7	-572	-569	-552	-564	-195	-211	-214	-207	-357
8/20	-558	-552	-554	-555	-172	-186	-192	-183	-372
9/3	-580	-580	-587	-582	-191	-203	-221	-205	-377
9/20	-587	-598	-610	-598	-188	-209	-222	-206	-392
9/28	-613	-609	-619	-614	-171	-185	-196	-184	-430
AVERAGE				-551					
AVE. 7/21 thru 9/28				-574				-203	-371

Note: All potentials are mV to the copper sulfate electrode. The positive meter lead was connected to the reinforcing steel.

Measurements taken after uncoupling mats (within 3 minutes).

TABLE 19.

Potentials for SLAB No. 105-79

VARIABLE: Both Mats Galvanized, w/c = 0.40

Date	Top Mat Potentials 1	2	3	Ave	Bottom Mat Potentials 1	2	3	Ave	Ave. Potential Diff.
4/20	-646	-673	-580	-633	-	-	-	-	-
4/21	-436	-540	-502	-493	-	-	-	-	-
4/22	-541	-624	-514	-560	-	-	-	-	-
4/27	-571	-676	-635	-627	-	-	-	-	-
4/28	-562	-671	-622	-618	-	-	-	-	-
4/29	-559	-653	-617	-610	-	-	-	-	-
5/7	-555	-635	-540	-577	-	-	-	-	-
5/12	-571	-645	-596	-604	-	-	-	-	-
5/19	-513	-592	-564	-556	-	-	-	-	-
5/29	-588	-708	-598	-631	-	-	-	-	-
6/11	-577	-712	-577	-622	-	-	-	-	-
6/23	-569	-692	-560	-607	-	-	-	-	-
6/29	-512	-626	-519	-552	-	-	-	-	-
7/1	-580	-707	-574	-620	-	-	-	-	-
7/10	-565	-726	-603	-631	-	-	-	-	-
7/21	-619	-702	-577′	-633	-386	-360	-355	-367	-266
7/27	-775	-838	-657	-757	-439	-375	-375	-396	-361
8/7	-800	-801	-635	-745	-448	-394	-379	-407	-338
8/20	-700	-763	-608	-690	-408	-354	-387	-383	-307
9/3	-645	-651	-558	-618	-416	-363	-402	-394	-224
9/14	-689	-702	-710	-700	-413	-387	-391	-397	-303
9/28	-686	-691	-616	-664	-383	-377	-406	-389	-275
AVERAGE				-625					
AVE. 7/21 thru 9/28				-687				-390	-297

Note: All potentials are mV to the copper sulfate electrode. The positive meter lead was connected to the reinforcing steel.

Measurements taken after uncoupling mats (within 3 minutes).

TABLE 20.

Potentials for SLAB No. 9-39

VARIABLE: w/c = 0.40 Black Steel

Date	Top Mat Potentials 1	2	3	Ave	Bottom Mat Potentials 1	2	3	Ave	Ave. Potential Diff.
4/20	-307	-361	-280	-316	-	-	-	-	-
4/21	-271	-316	-261	-283	-	-	-	-	-
4/22	-269	-310	-245	-275	-	-	-	-	-
4/27	-302	-333	-295	-310	-	-	-	-	-
4/28	-271	-325	-290	-295	-	-	-	-	-
4/29	-341	-298	-308	-316	-	-	-	-	-
5/7	-274	-356	-305	-312	-	-	-	-	-
5/12	-340	-388	-333	-354	-	-	-	-	-
5/19	-303	-357	-316	-325	-	-	-	-	-
5/29	-324	-366	-339	-343	-	-	-	-	-
6/11	-324	-362	-320	-335	-	-	-	-	-
6/23	-310	-371	-344	-342	-	-	-	-	-
6/29	-284	-331	-292	-302	-	-	-	-	-
7/1	-305	-365	-330	-333	-	-	-	-	-
7/10	-312	-359	-320	-330	-	-	-	-	-
7/21	-374	-392	-349	-372	-205	-176	-179	-187	-185
7/27	-392	-430	-374	-399	-198	-162	-185	-182	-217
8/7	-391	-413	-365	-390	-177	-165	-164	-169	-221
8/20	-410	-436	-368	-405	-212	-166	-182	-187	-218
9/3	-456	-398	-389	-414	-265	-170	-243	-226	-188
9/14	-426	-439	-386	-417	-225	-192	-214	-210	-207
9/28	-435	-431	-333	-400	-234	-174	-176	-195	-205
AVERAGE				-344					
AVE. 7/21 thru 9/28				-400				-194	-206

Note: All potentials are mV to the copper sulfate electrode. The positive meter lead was connected to the reinforcing steel.

Measurements taken after uncoupling mats (within minutes).

TABLE 21.

Potentials for SLAB No 77-38

VARIABLE: w/c = 0.50, Black Steel = Salt Free

Date	Top Mat Potentials 1	2	3	Ave	Bottom Mat Potentials 1	2	3	Ave	Ave. Potential Diff.
5/18	-160	-110	-120	-130	- 40	- 10	- 40	- 30	- 100
6/23	-170	-160	-150	-160	- 20	- 30	- 40	- 30	- 130
7/22	-160	-100	-110	-123	- 20	- 20	- 10	- 17	- 106
8/22	-140	-120	- 90	-117	- 40	- 50	- 20	- 37	- 80
AVERAGE				-133				- 28.5	- 104

Note: All potentials are mV to the copper sulfate electrode. The positive meter lead was connected to the reinforcing steel.

Measurements taken after uncoupling mats (within minutes).

TABLE 22.

Electrical Potential Taken Prior to Uncoupling the Mats

Slab Number	Variable	Electrical Potential, mV CSE Top Mat 1	Top Mat 2	Top Mat 3	Bottom Mat 1	Bottom Mat 2	Bottom Mat 3	Ave. Top Mat.	Ave. Bottom Mat.	Potential Difference mV
w/c = 0.50 concrete										
54-81	All Galvan.	-625	-600	-	-478	-380	-	-612	-429	-183
113-82	Top Mat Galvan.	-639	-588	-612	-282	-289	-331	-613	-301	-312
90-112	Black Steel	-524	-584	-607	-182	-67	-190	-572	-146	-426
99-15	Black Steel	-500	-637	-586	-206	-191	-281	-574	-226	-348
21-105	Black Steel	-566	-580	-610	-210	-250	-237	-585	-232	-353
w/c = 0.40 concrete										
105-79	All Galvan.	-675	-723	-595	-458	-391	-460	-664	-436	-228
9-39	Black Steel	-438	-446	-343	-245	-211	-150	-409	-202	-207
									Average =	285.5

10-2-81 mats coupled

TABLE 23.

Electrical Potential Taken After Uncoupling the Mats

Slab Number	Variable	Electrical Potential, mV CSE						Ave. Top Mat.	Ave. Bottom Mat.	Potentia Differenc mV
		Top Mat			Bottom Mat					
		1	2	3	1	2	3			
w/c = 0.50 concrete										
54-81	All Galvan.	- 671	- 610	-	- 421	- 358	-	- 641	- 390	- 251
113-82	Top Mat Galvan.	- 705	- 639	- 660	- 220	- 255	- 275	- 668	- 250	- 418
90-112	Black Steel	- 527	- 510	- 634	- 148	- 61	- 203	- 557	- 137	- 420
99-15	Black Steel	- 516	- 639	- 585	- 177	- 194	- 245	- 580	- 205	- 375
21-105	Black Steel	- 581	- 625	- 609	- 202	- 244	- 214	- 605	- 220	- 385
w/c = 0.40 concrete										
105-79	All Galvan.	- 699	- 717	- 631	- 435	- 388	- 414	- 682	- 412	- 270
9-39	Black Steel	- 457	- 479	- 375	- 233	- 223	- 180	- 437	- 212	- 225
									Average =	331

10-2-81 potentials taken immediately after uncoupling mats (completed within 2 minutes)

FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

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* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.

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