DIVISION OF STRUCTURES AND ENGINEERING SERVICES

TRANSPORTATION LABORATORY

RESEARCH REPORT

CORROSION OF STEEL IN CONCRETE

FINAL REPORT

FHWA-CA-TL-5351 76-49

DECEMBER 1976

76-49

Prepared in Cooperation with the U.S. Department of Transportation,

Federal Highway Administration

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CALIFORNIA DEPARTMENT OF TRANSPORTATION

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16. ABSTRACT

This report summarizes the findings presented in twelve individual interim reports. Of the twelve, four are concerned with field investigations of corrosion-damaged bridges, two with the evaluation of bridge deck membranes, and six with the general subject of laboratory corrosion testing.

For continuously salt water submerged reinforced concrete, the chloride ion contents varied from 13 to 34 pounds per cubic yard, with an average of 25 pounds per cubic yard. Calculations based on absorption determinations indicated that the concrete could have contained a 10% chloride solution while the bay water contained 1.7% chloride. Heavy corrosion of the reinforcing steel was observed in 47% of those piles inspected, with maximum pit depth ranging from 0.017 inch to 0.260 inch. The average maximum pit depth was 0.114 inch for pit lengths up to 6 inches.

The evaluation and study of corrosion-damaged bridges utilized chloride analysis of concrete samples, determination of metal loss of reinforcing steel samples, measurement of electrical potentials, the preparation of equipotential contour maps, and the determination of concrete delamination areas by sounding with chains.

(continued)

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16. Abstract (cont.)

Data were gathered from several salt-contaminated bridge decks that exhibited varying degrees of corrosion-caused distress. It appears that the presence of chloride changes the steel from a passive to an active state. Beyond a certain threshold amount (estimated to be one pound per cubic yard), additional amounts of chloride have little or no effect on the rate or amount of corrosion that takes place. Data indicate that the distribution of chloride in concrete is highly variable and that attention must be given to the number of samples required to determine the average chloride content of a concrete structure. A mathematical expression was derived which describes the distribution of chloride in concrete in relation to the depth below the concrete surface.

Although the half-cell potential of -0.35 v CSE indicates active corrosion, an equipotential contour map is the most reliable means of evaluating the corrosion activity of deck reinforcing steel. Chaining the deck surface has proved to be an effective means for locating concrete delaminations. When 10% of the half-cell potentials on a bridge deck indicated active corrosion or corrosion-caused distress exceeded 1% of the total deck area, the concrete chloride content was generally greater than one pound per cubic yard. Almost identical chloride contents were determined for concrete samples obtained by coring and by drilling.

Field and laboratory tests have indicated that the electrical resistance of a bridge deck membrane can be related to pinholes or other breaks in the membrane and, thus, to its sealing ability. In tests using electrical resistance as a membrane permeability indicator, it was found that the electrical resistance increased with time after application of the wetting solution.

Laboratory tests used to screen bridge deck membranes include elongation or crack bridging, puncture or the ability to withstand the application of a protective paving overlay, and bending or cold temperature ductility. Due to the short time of usage there is no established correlation between laboratory test results and actual membrane service life.

Laboratory corrosion tests have, in general, consisted of the partial immersion of reinforced concrete test specimens in a saturated sodium chloride solution. Data from such tests were statistically analyzed and mathematical relationships were derived that describe the influence of moist and steam curing, admixtures, mixing water, entrained air, and cement content on the time to corrosion of the embedded steel. Also determined were the steel corrosion loss and the concrete chloride content of typical test specimens. Test data indicated that increasing

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16. Abstract (cont.)

the cement factor and the length of the water curing period increased the time to active corrosion. Compared to water curing, steam curing resulted in a reduction of the time to corrosion and a reduction in concrete absorption. The addition of a pozzolan admixture appeared to produce a significant increase in the time to corrosion, but this concrete also exhibited the greatest absorption and drying shrinkage.

In laboratory tests, the half-cell potential of steel embedded in concrete specimens was periodically measured and related to the visual observation of concrete cracking. Although cracking was observed at a minimum level of -0.31 v, it was observed that when half-cell potential values were more negative than -0.42 v to the saturated calomel electrode (SCE), 50% of the reinforced concrete blocks were cracked due to the corrosion of the steel. At values between - 0.27 and -0.42 v SCE, the steel was corroding but not always enough to cause concrete cracking. For cracked specimens, the maximum half-cell potential of the steel was -0.59 v SCE.

Laboratory tests were conducted on concrete specimens to determine the effect of moisture content, absorption, and added chloride on the electrical resistivity of concrete. Data indicated that the addition of salt has no direct effect on the electrical resistivity, but that it does increase the absorption of the concrete. With other factors constant, concrete absorption is increased by increasing the mixing water, reducing the cement content, and by adding calcium chloride.

An analytical procedure was developed that will permit cost savings by terminating tests after a given percentage of the samples have reached a specific corroding condition.

Concrete test specimens containing galvanized and black reinforcing steel were partially immersed in a saturated salt solution. The results were: (1) corrosion began at about the same time for both the galvanized and black (mild) steel exposed in the same concrete system; (2) the greater the thickness of zinc, the earlier concrete cracking occurred; and (3) in concrete of high quality, galvanized steel caused concrete cracking earlier than black steel. Thus, for these particular tests, galvanizing was ineffective as a galvanic anode to prevent rusting of the underlying steel in concrete. In salt contaminated concrete zinc behaves similarly to steel; it corrodes and causes concrete cracking.

The most significant variable in postponing concrete cracking caused by corrosion of black or galvanized steel was to increase the cement factor.

There does not appear to be a half-cell potential value per se, that would disclose the corrosion activity of galvanized steel in concrete.

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STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF STRUCTURES & ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY

December 1976

FHWA No. D-3-11
TL No. 635351

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this final research project report titled:

CORROSION OF STEEL IN CONCRETE

Study made by . . . . . Roadbed & Concrete Branch

Under the Supervision of . . . . . D. L. Spellman

Principal Investigator . . . . . R. F. Stratfull

Report Prepared by . . . . . F. A. Myhres

Very truly yours,

George A. Hill

GEORGE A. HILL
Chief, Office of Transportation Laboratory

Attachment

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ACKNOWLEDGEMENT

The contents of this report reflect the views of the Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Many people have been involved in this research project during the past twelve years. As Chief, Transportation Laboratory, J. L. Beaton and G. A. Hill have provided advice and general direction during this study. Also, special thanks must go to the following persons who have been involved in one or more of the twelve studies. Although several have retired or changed jobs, the alphabetical lists reflect the associated organization at the time that assistance was provided.

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INTRODUCTION

This research project was initiated in October 1964, as a result of increasing bridge repair costs due to corrosion of the reinforcing steel. The initial objective was to develop the "means whereby reinforced concrete structures can be designed for a specific maintenance-free service life". As work progressed and data were accumulated, the objective was modified to include consideration of "concrete quality, absorption, mix variables, thickness, and chloride content as they may influence the time to corrosion of embedded steel. These factors will be researched and design measures will be developed to control the corrosion of steel in concrete."

At the time the original research proposal was prepared (1964), the indicated steel corrosion problem concerned bridge substructures. Generally, with minor deck problems, surveys of both coastal bridges in 1956 and desert bridges in 1959 showed that a significant number of structures were affected by the corrosion of reinforcing steel. In addition, corrosion damage was one of the major reasons for replacing, rather than widening, the San Mateo-Hayward Bridge. These were the basic factors that prompted the initiation of this research project.

Subsequently, the results of California's "bare pavement" policy began to show up on bridge decks. Large quantities of deicing salts were being applied to bridge decks to prevent frost formation and to melt snow and ice. A committee which was formed to determine the magnitude of the problem estimated that as many as 1000 bridge decks might require some $30,000,000 to repair and correct corrosion-caused damage.

Thus, although the basic problem remained the same - corrosion of steel in concrete -, the magnitude and extent of that problem increased dramatically during the intervening period.

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During the existence of this research project, twelve individual interim reports have been written. The following is a list of these reports and the associated publication information.

1. "Corrosion of Steel in Continuously Submerged Reinforced Concrete Piling", Highway Research Board, National Academy of Sciences, Highway Research Record No. 204, 1967.

2. "The Effect of Added Chloride on the Resistivity and Absorption of Mature Concrete", Presented at the 23rd Annual Conference, National Association of Corrosion Engineers, Los Angeles, California, March 1961, Research Report No. M&R 635116-2.

3. "Laboratory Corrosion Test of Steel in Concrete", M&R 635116-3.

4. "Chlorides and Bridge Deck Deterioration", Highway Research Board, National Academy of Sciences, Highway Research Record No. 328, 1970.

5. "Method for Reducing the Cost of Corrosion Testing of Reinforcing Steel", M&R 635116-5.

6. "An Electrical Method for Evaluating Bridge Deck Coatings", Highway Research Board, National Academy of Sciences, Highway Research Record No. 357, 1971.

7. "Concrete Variables and Corrosion Testing", Highway Research Board, National Academy of Sciences, Highway Research Record No. 423, 1972.

8. "Half Cell Potentials and the Corrosion of Steel in Concrete", Highway Research Board, National Academy of Sciences, Highway Research Record No. 433, 1973.

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9. "Corrosion Autopsy of a Structurally Unsound Bridge Deck", Highway Research Board, National Academy of Science, Highway Research Record No. 433, 1973.

10. Bridge Deck Membranes, Evaluation and Use in California", Presented at AASHO Session on Materials - 59th Annual AASHO Convention, Los Angeles, Research Report No. CA-DOT-TL-5116-9-73-38, 1973.

11. "Corrosion Testing of Bridge Decks", Transportation Research Board, National Academy of Sciences, Transportation Research Record No. 539, 1975.

12. "Laboratory Corrosion Tests of Galvanized Steel in Concrete", Presented at 55th Annual Meeting of the Transportation Research Board, National Academy of Sciences, Washington, D.C., Research Report No. CA-DOT-TL-5351-1-76-02, January 19, 1976.

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SUMMARY OF CONCLUSIONS IN THE INTERIM REPORTS

Report #1. CORROSION OF STEEL IN CONTINUOUSLY SUBMERGED REINFORCED CONCRETE PILING

A. Significant corrosion was evident in 47% of those piles that were inspected.

B. There was very little difference in the chloride content of concrete in areas of light and heavy corrosion. Concrete chloride ion content varied from 13 to 34 lb per cu yd and averaged 25 lb per cu yd.

C. Corrosion did occur in continuously submerged piling.

D. From absorption measurements, it was calculated that there could be a 10% chloride solution in the concrete while the bay water contained 1.7% chloride.

Report #2. THE EFFECT OF ADDED CHLORIDE ON THE RESISTIVITY AND ABSORPTION OF MATURE CONCRETE

A. A highly absorptive concrete could result in accelerated corrosion of embedded steel.

B. With other variables constant, concrete absorption is increased by increasing the amount of mixing water, reducing the cement content, and by adding calcium chloride.

C. Except for the condition of oven drying and resoaking, there was no change in concrete electrical resistivity as a result of adding calcium chloride to the mix.

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Report #3. LABORATORY CORROSION TESTS OF STEEL IN CONCRETE

A. There is a definite relationship between time to corrosion and time to corrosion-caused concrete cracking.

B. Time to an active potential is increased by reducing the mixing water and increasing the cement content.

C. Half-cell potential values less negative than -200 mv to a saturated calomel electrode (SCE) indicate a passive steel condition.

Report #4. CHLORIDES AND BRIDGE DECK DETERIORATION

A. An analysis of data concerning the distribution of chloride in concrete indicates that for each additional inch of depth, the chloride content decreases approximately one-half.

B. Examination of reinforcing steel from a distressed bridge deck revealed that, although the metal loss due to corrosion was not yet structurally significant, there was sufficient corrosion to cause concrete cracking.

C. Corrosion-caused deterioration of a bridge deck can be averted or postponed by using a noncorrosive deicing chemical or by installing a waterproof membrane on the deck surface.

D. Half-cell potential measurements can be used to locate corroding steel in bridge decks and may be used to evaluate repair techniques that are believed to arrest steel corrosion.

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Report #5. METHOD FOR REDUCING THE COST OF CORROSION TESTING OF REINFORCING STEEL

A. If an adequate number of specimens are tested, a censored sample will provide results equivalent to those obtained from an uncensored sample.

B. Application of the developed procedure to actual data indicated a reduction of up to 50% in testing could be realized.

Report #6. AN ELECTRICAL METHOD FOR EVALUATING BRIDGE DECK COATINGS

A. The electrical resistance of a bridge deck coating provides a relative indication of the coating's waterproofing ability.

Report #7. CONCRETE VARIABLES AND CORROSION TESTING

A. Concrete absorption per se does not seem to be a reliable indicator of corrosion resistance.

B. Electrical potential values less negative than -0.22 v SCE indicate a passive steel condition, while values more negative than -0.27 v SCE indicate an active steel condition.

C. The time to corrosion of embedded steel increases as the cement factor is increased.

D. The time to corrosion for steam cured concrete was about 60% of that for water cured concrete.

E. The addition of a calcined volcanic tuff pozzolan resulted in a significant increase in the time to corrosion and, in combination with steam curing, produced an apparently greater benefit in a short period of time. The steam curing is thought to be of benefit because it increased the rate of hydration of the pozzolan.

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Report #8. HALF CELL POTENTIALS AND THE CORROSION OF STEEL IN CONCRETE

A. Electrical potential measurements can indicate passive and active steel conditions.

B. Differences in electrical half-cell potentials are associated with the "solution potential" of the steel and the voltage gradients resulting from current flow.

C. To detect corrosion-caused electrical current, it is not always necessary to physically connect the meter to the embedded steel.

Report #9. CORROSION AUTOPSY OF A STRUCTURALLY UNSOUND BRIDGE DECK

A. Although the electrical potential measurements detected steel corrosion not yet indicated by concrete distress, they are not considered to be a reliable indicator of the rate or amount of corrosion.

B. Sounding with a chain is an effective and practical means of locating concrete delaminations.

C. Metal loss cannot be accurately predicted by a visual evaluation of the surface condition of corroding steel.

D. Beyond the critical amount required to destroy steel passivity, the chloride content per se does not influence the incidence or rate of corrosion.

Report #10. BRIDGE DECK MEMBRANES, EVALUATION AND USE IN CALIFORNIA

A. In general, laboratory screening tests have reasonably predicted initial field performance of bridge deck coatings.

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Report #11. CORROSION TESTING OF BRIDGE DECKS

A. The chloride content of reinforced concrete associated with active steel corrosion is one lb. per cu. yd. of concrete.

B. The chloride contents of identical concrete samples were about equal for test specimens obtained by coring and by drilling.

C. Data confirmed that electrical potentials more negative than -0.35 v CSE indicate active corrosion.

D. A random half-cell potential survey appears to be a satisfactory procedure when the corrosion activity of numerous structures must be determined.

Report #12. LABORATORY CORROSION TESTS OF GALVANIZED STEEL IN CONCRETE

A. It appears that zinc behaves similarly to steel in salt-contaminated concrete; it corrodes and causes concrete cracking.

B. As determined by previous studies, the resulting time to corrosion for steam cured specimens was less than that for water cured specimens.

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TEST SPECIMENS AND PROCEDURES

The research studies summarized in this report made use of several types of specimens for laboratory testing. Most commonly used were absorption test cylinders and corrosion test blocks.

The variations in concrete mix design are listed in the individual reports. In general, the cement used was Type II, modified, low-alkali which complied with the California Standard Specifications. The 3/4 in. max, river-run aggregate complied with the requirements of the Standard Specifications for quality and gradation. Steel specimens, either #4 rebar or 1/2 in. diameter round bar of the desired quality, were sandblasted prior to fabrication.

The absorption test specimens used in the studies were 6 in. by 6 in. concrete cylinders. Testing was in accordance with Test Method No. Calif. 538, in which weight gain due to absorption is reported as a percent by volume of the concrete.

The corrosion test specimens consisted of a 1/2 in. diameter by 17 in. long steel specimen cast in a 4-1/2 in. by 2-1/2 in. by 15 in. long concrete block. The steel bar was centered in the 4-1/2 in. by 2-1/2 in. face of the block and positioned to provide a minimum concrete cover of one inch.

Those specimens to be steam cured were allowed to remain in the casting molds for a minimum of four hours and then subjected to 16 hours of steam curing at 138 $\pm$ 5°F. The blocks were then completely submerged in water at 72°F for the balance of the curing period. Those specimens to be water cured were completely submerged in water at 72°F for the entire curing period.

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Immediately following curing, the blocks were transferred to the partial immersion tanks for corrosion exposure. The blocks were oriented so that the steel bar was in a vertical position. Specimen density in the partial immersion tanks was approximately 6 specimens per sq ft. A saturated sodium chloride solution was maintained at an empirically selected depth of 3-1/2 in. A steel binding post was installed on each specimen to make an electrical connection from the steel bar to a voltmeter. Electrical half-cell potentials, referenced to a saturated calomel electrode (SCE), were measured thrice weekly. The potentials were measured and recorded on both paper and tape by an automatic voltmeter and data acquisition system. After active corrosion began (indicated by a "potential jump"), the specimens were briefly removed from the tank at regular intervals and visually inspected for concrete cracking.

For some studies a complete photographic record of each specimen was made after corrosion exposure testing was discontinued. This included photographs of visible evidence of corrosion on the concrete surface and on the steel specimen after removal from the concrete block. In addition, samples of concrete were removed from typical test blocks and chemically analysed for chloride content.

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INDIVIDUAL REPORT SUMMARIES

The subject of steel corrosion in reinforced concrete structures naturally divides into two basic problems. The first, concerning new construction, requires that we learn what actions can be taken to maintain the passivity of the embedded steel for an extended period of time. Such actions would include, but not necessarily be limited to, (1) improve concrete quality and increase cover, (2) apply waterproof membranes, (3) design impervious concrete, (4) suspend the application of deicing salts and/or use noncorrosive deicers, (5) apply cathodic protection, and (6) apply coatings to the steel to isolate it from the aggressive environment.

The second problem has to do with the maintenance and repair of structures already in existence. Developed procedures must be used to accurately evaluate bridge condition from a corrosion standpoint. Such an evaluation is necessary to provide the basis for a choice of the most beneficial course of action to arrest or prevent steel corrosion.

This report summarizes twelve individual studies conducted under the broad subject of this research project. Although the titles seem to indicate a wide range of topics, they all share a common purpose. Each was concerned with steel corrosion in reinforced concrete and/or sought to determine those conditions or parameters that postpone corrosion of embedded steel for the longest period of time. Therefore, each study was concerned with one or both of these basic problems.

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"CORROSION OF STEEL IN CONTINUOUSLY SUBMERGED REINFORCED CONCRETE PILING"

The object of this study was to ascertain the existence of steel corrosion in continuously submerged reinforced concrete, and to gather further data concerning the quantity of chloride in concrete that causes the corrosion of embedded steel.

This report describes the findings of the inspection and sampling of the submerged portions of 17 reinforced concrete piles. These piles had been continuously submerged in San Francisco Bay for approximately 37 years.

Construction records indicate that the concrete had an average cement factor of 6.9 sacks per cu yd, an average slump of 3 in. to 5 in., maximum aggregate size of 1-1/2 in., and contained a well graded sand that had a fineness modulus of about 2.8. It is estimated that the water-cement ratio was about 5.7 gal per sack of cement. Compressive strengths for 170 test cylinders were reported to be in the 4000-5000 psi range.

Observation and sampling of the piles took place immediately following their removal. After visually inspecting and photographing the exterior pile surface, the steel at one corner was exposed and removed. Fragments of the concrete were identified and retained for laboratory analysis. The steel was immediately inspected for any evidence of corrosion and then a section extending approximately 3 feet in each direction from the mud line was removed. Corrosion pit depth was determined by means of a micrometer. Laboratory testing determined the chloride content and seven-day absorption of the concrete samples removed from each pile.

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Results of the chloride analysis varied from 13 to 34 lb of chloride ion per cu yd of concrete with an average of 25 lb per cu yd. The reported values indicate the average chloride content for the total depth of cover over the steel which varied from 1-1/4 in. to 2-1/2 in. The average seven-day absorption was the equivalent of 255 lb of water per cu yd with extreme values of 227 and 298. For the eight steel samples that exhibited significant corrosion, maximum pit depth varied from 0.017 in. to 0.260 in. and averaged 0.114 in. In general, maximum pit depth occurred at the mud line; however, significant corrosion was also noted in the submerged portions of the piles. Based on these test results, it is estimated that the concrete exposed to free water could have contained a 10% chloride solution, while the bay water contained 1.7% chloride.

This study did not determine the mechanism of steel corrosion in the submerged portions of these piles. However, it was demonstrated that for this particular salt-contaminated concrete and about 2 inches of cover, corrosion occurred in continuously submerged sections of the piling.

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"THE EFFECT OF ADDED CHLORIDE ON THE RESISTIVITY AND ABSORPTION OF MATURE CONCRETE"

A previous study of the San Mateo-Hayward Bridge showed that concrete cracking was negligible in areas where the electrical resistivity of the concrete was greater than 65,000 ohm cm. These data also indicated that, for salt-contaminated concrete, cracking is not related to salt content, but rather, that the rate of corrosion and/or concrete deterioration is primarily controlled by the electrical resistivity of the concrete. The purpose of this study was to determine the relative influence of moisture content, absorption, and added chloride on the electrical resistivity of concrete.

The sixty test specimens used for this study were 5 in. by 6 in. by 12 in. concrete blocks with a piece of copper mesh cast into the 5 in. by 6 in. ends. Twenty different mix combinations were produced by varying the water-cement ratio, cement factor, and chloride content. For all mixes, the coarse aggregate volume was held constant while the sand volume varied with the cement factor. As the cement content increased, the sand was decreased.

After the blocks were cast, they were cured at 73.4°F and 100% humidity for 20 months. Following this curing period was a total testing period of 112 weeks duration. Covered by a canvas cloth, the blocks were maintained in laboratory air for the first 111 weeks. At the beginning of, and periodically throughout, this 111 week period, the weight and electrical resistivity of the individual blocks were determined. During the 112th and final week of testing, the blocks were oven dried for 24 hours at 230°F and then submerged in water for 48 hours. Immediately following the submersion period, final weight and electrical resistivity determinations were made for each block.

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Data gathered in this manner were analysed statistically and mathematical formulas were derived which describe relationships between chloride content and concrete absorption, and between water voids, cement factor, and mixing water. In addition to the formulas, the associated indicators of statistical significance, correlation coefficient, standard error of estimate, and level of significance were also reported. In general, these analyses indicate that, with other factors held constant, the absorption or evaporable water content of concrete increases with increasing quantities of mixing water, decreasing amounts of cement, and increasing amounts of calcium chloride.

With the following exception, the addition of varying amounts of calcium chloride produced no significant difference in electrical resistivity of the test specimens. After the 24 hour oven drying and 48 hour soaking periods, the data indicated that the addition of chlorides did produce a significant reduction in electrical resistivity. It was not clear why the change in resistivity occurred after the concrete was oven-dried.

Data accumulated during the 111 week period when the specimens were stored and drying in laboratory air indicated that concrete resistivity is dependent on the evaporable water content of the concrete and the relative amount of water contained in the same concrete. With equal degrees of saturation, the concrete with the highest absorption will have the lowest specific electrical resistance.

These data also showed that the amount and rate of moisture loss varied for each of the mixes. The rate of moisture loss increased with greater concrete absorption. Thus, specimens with higher concrete absorption dried to an electrical resistivity of 65,000 ohm cm (noncorrosive level of dryness) more rapidly than specimens with a lower absorption.

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For the variables tested, these data also indicated that absorption controls the rate at which concrete accumulates chloride from its environment. As the water evaporates and leaves the salt behind, each wetting and drying cycle increases the chloride content of the concrete. This process will be more rapid for a concrete with a higher absorption which gains and loses water more readily than concrete with a lower absorption.

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"LABORATORY CORROSION TEST OF STEEL IN CONCRETE"

The purpose of this investigation was to determine the relative effect of common design variables on the corrosion resistance of reinforced concrete and to evaluate a particular procedure for the corrosion testing of reinforced concrete.

Results of this study indicate that corrosion testing of reinforced concrete specimens by partial immersion in a saturated sodium chloride solution is related to the probable performance of bridge substructures in California environments. The relationship considers the variable of chloride concentration both in the environment and in the laboratory. Test results indicate a mathematical relationship between the time to an active potential and the time to corrosion-caused cracking of the reinforced concrete. In general, the time to an active potential was increased by reducing the mixing water or by increasing the cement content. The time to an active potential was decreased by steam curing, increasing the mixing water, and reducing the cement content. The data also indicated that the net result of water-reducing, set-retarding, and air-entraining admixtures can be beneficial if their use allows a reduction in mixing water. The most probable maximum value for a passive half-cell potential of steel in aged concrete is estimated to be about 200 mv negative to a saturated calomel electrode.

With two exceptions, test specimens and procedure followed the description in the previously outlined test specimens and procedures section. Twenty batches of ten test blocks each were fabricated with one set of five blocks used for each variable. Design variables included cement factor, fineness modulus, curing method, concrete slump, steel in vertical or horizontal position during casting, and three types of admixture. The exceptions noted above were: (1) after curing, the specimens were stored in laboratory

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air (72°F and 50% relative humidity) for 10.5 months, and (2) a 5-1/2 month period of partial immersion in varying depths of fresh water preceded the partial immersion testing in 3-1/2 in. of saturated sodium chloride solution.

After all five blocks in a set exhibited rust stains or cracking, the set was removed from the test. Maximum corrosion pit depth was determined for each rebar, each concrete specimen was sampled for chloride analysis at four levels, and a complete photographic record was made of all visible evidence of corrosion on the concrete and steel.

The data were analysed by statistical methods and formulas were developed to describe the effect of the design variations. In general, the following variables seem to significantly affect corrosion test results: (1) number of samples, (2) moisture content of the concrete at the time of initial immersion, (3) temperature, (4) relative humidity, (5) solution salinity, and (6) ratio of sample surface area to volume. It appears that half-cell potential measurements that indicate the change from a passive to an active condition may be more significant and definitive than visual corrosion evidence.

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"CHLORIDES AND BRIDGE DECK DETERIORATION"

The object of this study was to determine the level of chloride in concrete that can cause corrosion of reinforcing steel. The need for such a study was indicated in 1969 by the advertising of three construction contracts to repair and resurface a total of 31 bridge decks. A survey of California bridge decks in 1962 had indicated that no significant deck deterioration problem existed. This rapid increase in deck deterioration was accompanied by a rather dramatic increase in the use of deicing salts - from 3000 tons in 1960 to an estimated 10,000 tons in 1968.

Results of the chloride analyses were used to determined the basic mathematical relationship between chloride content and depth below the deck surface. This relationship, which indicates that the chloride content varies inversely with depth, was confirmed by similar data for samples from the submerged portions of San Mateo-Hayward bridge piles. Statistical analysis also indicated that a minimum of six samples should be obtained to estimate the average chloride content of any bridge deck.

A sample of steel removed from one distressed deck was analysed for corrosion loss in each foot of length. The maximum loss detected was not structurally significant, but was more than enough to cause concrete cracking and spalling.

Half-cell electrical potentials taken on two decks indicated that distress is associated with corrosion as indicated by the electrical measurements. Such measurements can be utilized to locate areas of active corrosion and to evaluate repair techniques that are thought to arrest corrosion.

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The main source of data for this study was the chloride analysis of concrete cores. The number of cores obtained from each bridge deck varied from 6 to 22. The cores were sawed into one inch layers and the average chloride content for each layer was determined. Cores from continuously submerged piles were obtained and treated in the same manner. Statistical analyses were performed to derive the relationship between depth and salt content, to determine the reliability of this relationship, and to equate the number of samples obtained with the resulting sampling error.

Half-cell electrical potentials were measured on twin parallel spans; one exhibiting minor surface distress and the other with extensive deterioration. Potentials, referenced to a copper-copper sulfate half-cell, were taken on a two foot grid and used to prepare an equipotential contour map of each deck.

A total of 47 lineal feet of corroded reinforcing steel was removed from a single bridge deck. After a light sandblasting, a micrometer was used to determine the maximum metal loss for each lineal foot.

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"METHOD FOR REDUCING THE COST OF CORROSION TESTING OF REINFORCING STEEL"

The object of this study was to develop a statistical procedure of censored sampling for normal distributions that can be applied to corrosion testing of reinforced concrete. The problem was to develop a procedure that would permit testing to be terminated either after the testing of a given percentage of specimens was completed or after a given number of test days had elapsed. In addition, it was desired to obtain an estimate of the expected error for the reduced testing results and to determine the number of additional test specimens that would be required in order to insure that the reduced sample test results be equivalent to uncensored sample results.

A present method of corrosion testing makes use of reinforced concrete specimens partially immersed in a saturated sodium chloride solution. At some point, the passivity of the steel is destroyed and corrosion of the steel begins. This condition is indicated by a significant increase in potential ("potential jump") between the reinforcing steel and a standard reference cell. The elapsed time period for this event to occur varies widely for identical specimens and may be as long as several hundred days. Therefore, considerable savings in testing and personnel time would be possible and earlier decisions would result from a procedure that could extrapolate reliable supplemental data from the results of a censored sample.

The required procedure was developed and the mathematical derivation is presented in the interim report. Also included is a method for determining the number of additional specimens required for various reductions in testing time, an estimate of the error resulting from censored tests, and an example of the procedure applied to actual test results. The procedure was

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applied to eight sets of actual data in order to demonstrate its validity. It is estimated that approximately 50 percent of such testing can be curtailed, thus, resulting in substantial cost savings.

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"AN ELECTRICAL METHOD FOR EVALUATING BRIDGE DECK COATINGS"

Waterproof membranes are applied to prevent the intrusion of salt water into bridge deck concrete and the subsequent steel corrosion associated with salt-contaminated reinforced concrete. This report presents a method of evaluating the integrity of such a membrane by measuring its electrical resistance. While such a procedure has previously been used for pipeline coatings, it is relatively new for bridge decks.

This method measures the resistance of the membrane by means of an ordinary ohmmeter with one lead connected to a surface plate and the other to the deck rebar. Since moisture conditions of both the concrete and overlay affect measurements, readings are reproducible only in broad terms. However, this is satisfactory since it is estimated that an excellent membrane will always have an electrical resistance greater than 500,000 ohms per sq ft; while a poor or perforated membrane will never have a resistance in excess of 100,000 ohms per sq ft.

In order to determine the effect of membrane perforations, tests were conducted on bridge decks coated with a coal tar modified epoxy resin (Specification 701-80-35). Test locations were selected that had an initial resistance in excess of 8,000,000 ohms per sq ft. This coating was then perforated with various size holes and the electrical resistance was remeasured. These data were analysed statistically and equations were derived that relate hole area to measured resistance. Typical resistance values for other coatings are also presented in the report.

Although the gross electrical resistance as determined by this method is not a precise figure, it can be used as an indicator of coating porosity. Thus, it is felt that such measurements will provide valuable information for the evaluation of new membrane installations. It is possible that as data are accumulated a correlation may be developed to relate electrical resistance with membrane field performance.

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"CONCRETE VARIABLES AND CORROSION TESTING"

The objective of this study was to determine the influence of variation in certain design factors on the corrosion resistance of reinforced concrete. An earlier report, "Laboratory Corrosion Test of Steel in Concrete", had indicated the need for additional data. The report contains the supplemental data concerning curing methods, cement factor, and admixtures - two corrosion inhibitors and one pozzolan.

The test procedure, with one exception, was the same as that used in the earlier study. The half-cell potential (referenced to a saturated calomel cell) of reinforced concrete blocks partially immersed in a saturated sodium chloride solution was measured three times each week. The end of the passive period or time-to-corrosion of the embedded steel was indicated by a significant increase in potential. No visual observations were made to detect rust stains or concrete cracking. This omission was the only departure from the previous test procedure. Additional data were accumulated by determining absorption and drying shrinkage for each of the 71 batches of concrete.

Test results again demonstrated that steam curing reduces the length of the passive period. The average passive period for steam cured specimens was approximately 60% of that for the water cured specimens. Increased curing time was found to increase the time-to-corrosion. Statistical analysis of the data indicated that, for these tests (6 sack concrete with curing periods varying from 2 through 32 days), doubling the water curing duration increased the passive period by about 50% for both the steam and water cured specimens.

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Increasing the cement factor (for the range of five to eight sacks per cu yd) increased the time-to-corrosion of the steel. A regression analysis of these data indicated that the passive period can be lengthened by approximately 70% by a cement factor increase of one sack per cu yd when used in conjunction with a lesser water/cement ratio.

The addition of hydrated lime to the concrete mix did not produce any significant change in the passive period. The addition of the other corrosion inhibitor, sodium benzoate, did result in a marked increase in the passive period. However, use of this admixture also resulted in a sizable reduction in mixing water, so it is not known whether the benefit is due to the admixture or to the water reduction. The addition of calcined volcanic tuff pozzolan also significantly increased the passive period. Although, the effect of pozzolan was greater for steam cured concrete, the statistical analysis indicated that a longer curing period might produce increased benefits for water cured concrete containing pozzolan.

The evaluation of concrete absorption as an indicator of corrosion resistance proved partially inconclusive. Absorption was reduced by increasing the cement factor which increased the time-to-corrosion. Absorption was also reduced by steam curing which reduced the time-to-corrosion. Thus, while absorption may be of value for evaluating similar concrete mixes, its worth as a corrosion resistance indicator of different concrete mixtures is doubtful.

No particularly significant corrosion information was derived from the drying shrinkage tests, however, the purpose of the shrinkage tests was to evaluate side effects resulting from the use of additives.

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"HALF CELL POTENTIALS AND THE CORROSION OF STEEL IN CONCRETE"

The objectives of this study were to attempt to find a half-cell potential value that is indicative of the amount of steel corrosion that can cause concrete to crack, and to explore some of the various techniques used to obtain half-cell potentials. Data were obtained from two different series of tests. In one series, half-cell potentials were recorded for reinforced concrete specimens partially immersed in a saturated sodium chloride solution. The second series consisted of measuring half-cell potentials and potential gradients on the surface of a corroding simulated bridge deck. Four different techniques used to measure potentials on the bridge deck illustrate that the level of measured potential is affected by the selected reference electrical ground.

Corrosion test block fabrication and test procedure followed the description outlined previously.

Data from the corrosion test blocks demonstrate that half-cell potentials can be a useful tool for evaluating reinforced concrete structures exposed to an aggressive environment. Potential values less negative than -0.22 v to the saturated calomel electrode (SCE) indicate a passive condition; and values in the -0.27 to -0.42 v SCE range would indicate corrosion activity that is not likely to cause concrete distress. There is a probability (in excess of 50%) that, for potential values more negative than -0.42 v SCE, good quality concrete cover of one inch will have been cracked.

The simulated bridge deck was fabricated in accordance with the requirements for a six foot effective span as listed in the Bridge Planning and Design Manual. Other than a reduction of 1/2 in. in concrete cover for the top steel, the slab was exactly the same as the interior portion of an actual bridge

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deck designed for a six foot span. The quality, composition, and placement of the concrete and steel complied with the Standard Specifications. Corrosion of the reinforcing steel was promoted by the application of salt and water to the slab surface, with alternate wet and dry periods.

Four separate sets of electrical potential readings were measured on the simulated deck surface. The voltmeter used to measure the potentials was grounded sequentially in the following manner: (1) all of the slab reinforcing steel; (2) a single, long, electrically isolated reinforcing bar in the slab; (3) an electrically isolated steel probe embedded in the slab at a depth of 4 in.; and (4) a saturated calomel electrode which was left in place on top of the slab. These readings were used to prepare four equipotential contour maps of the test slab. Although the maps display great similarity in the location and shape of contours, the potential values are very different. Regardless of the selected potential reference and whether or not a direct electrical connection was made to the reinforcing steel, the same corrosion-caused voltage gradients were measured on the concrete surface. However, the level or numerical value of the measured potential is dependent upon the chosen reference.

Based on the data acquired from the simulated slab, the following conclusions can be drawn: (1) Electrical potential measurements can indicate an active or passive steel condition. (2) Differences in the electrical half-cell potentials are associated with the "solution potential" of the steel as well as the voltage gradients resulting from current flow. (3) In a voltage gradient, the measured half-cell potential may not necessarily reflect the true half-cell potential of the most proximate steel because the voltmeter can only indicate the highest voltage at that point. For example, two pieces of steel may be in proximity to the point of measurement; one may be corroding and the other not.

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The voltmeter will indicate the highest voltage present and, thus, there will be no indication of the presence of the non-corroding steel. (4) To detect corrosion-caused electrical current flow, it is not alway necessary to electrically connect the voltmeter to the reinforcing steel. (5) The best measure of the electrical half-cell potential is obtained from a direct electrical connection to the steel under consideration.
(6) Under the conditions of electrical current flow, all half-cell potential measurements will be distorted by the arithmetic difference of the associated voltage gradients.

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"CORROSION AUTOPSY OF A STRUCTURALLY UNSOUND BRIDGE DECK"

This report contains the findings of a comprehensive corrosion evaluation of a bridge deck that had become structurally unsound and required replacement. This evaluation was based on data provided by electrical potential measurements; chaining the deck to locate areas of delamination; determining the chloride content, absorption, and compressive strength of the deck concrete; and the search for a relationship between rust amounts and metal loss.

A four foot reference grid was laid out on the deck and the delaminated areas were located by chaining. Delaminated areas, deck patches, and an area supported by false work were outlined on the deck with paint and also plotted on a deck layout sheet. Electrical potential was measured at each point on the grid. Twenty-two 4 in. diameter cores were taken from deck areas representing various stages of concrete distress. Many observations and measurements were made as large sections of the deck were removed. A detailed corrosion record was made of the reinforcing steel contained in three 7 by 12 ft sections that were removed from the deck. These sections represented an area of minor delamination and cracking, an area that had severe soffit cracking and many epoxy patches on the deck surface, and the area that was structurally unsound and supported by false work.

The deck cores were returned to the laboratory for testing and analysis. Four cores that contained neither steel nor epoxy mortar were tested for absorption and compressive strength. All cores were cut into one inch slices and an average chloride content was determined for each inch of depth.

The reinforcing steel removed from the three deck sections was visually rated for the amount or degree of corrosion. Then, randomly selected pieces were sandblasted and maximum pit depth was determined.

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Electrical potential measurement provided a more accurate indication of the extent of steel corrosion than chaining the deck for delaminated areas. About 20% of the total deck area was delaminated while 94% of the potentials were in the active range (-0.35 v to -0.55 v CSE).

The attempt to relate external corrosion indications with actual pit depth was unsuccessful. The poor correlation suggests that metal loss should actually be measured rather than estimated by rust thickness.

Although the relatively high porosity and absorption of the concrete were contributing factors, the principle cause of deck failure was the application of deicing salts. The absorption of the salts resulted in corrosion of the steel which, in turn resulted in concrete delamination. The delamination reduced the thickness of the structural section to a point where the live traffic load caused the last stage of failure by fatigue.

Analysis of the concrete cores indicated that compressive strength was lower and absorption was higher than would normally be expected for concrete of this age and design. There did not seem to be any relationship between chloride content and deck deterioration. It appears that after the chloride level that destroys steel passivity is reached, the corrosion rate is most dependent on the moisture content of the concrete.

In general, electrical potential measurements and chloride analysis appear to be the most valuable indicators of the extent and level of corrosion activity. For determining the actual condition of deck concrete, chaining provides the easiest and most rapid technique for locating undersurface fractures and spalls.

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"BRIDGE DECK MEMBRANES, EVALUATION AND USE IN CALIFORNIA"

Waterproof membranes are applied to bridge decks to prevent the entrance of deicing salts and the subsequent corrosion of reinforcing steel. A test method to evaluate membrane waterproofing ability has been developed that can be used in the laboratory or field with equal success. The report describes this test method and other procedures tentatively used for laboratory membrane evaluation, and compares the field performance of some waterproof membranes with the laboratory test results.

Preliminary laboratory evaluation consists of determining a membrane's ability to: (1) span a crack, (2) resist puncturing during placement of an AC overlay, and (3) resist heat aging. These three characteristics are evaluated by the tension test, puncture test, and bend test, respectively.

In the tension test, the membrane is applied to the surface of a 6 in. by 12 in. concrete block. If the electrical resistance of the membrane exceeds 500,000 ohms, the specimen is conditioned at -5°F for at least 12 hours. The block is then fractured to a crack opening of 0.1 in. If the membrane appears to have successfully spanned the crack, the test specimen is allowed to come to room temperature. Then the electrical resistance of the membrane is measured to confirm that the membrane has maintained its integrity while spanning the crack.

The puncture test makes use of another 6 in. by 12 in. concrete block. After the membrane has been applied, asphalt concrete (AC) at 300°F is placed and compacted with a pre-heated hand roller. The resistance of the membrane after the overlay is compacted is required to exceed 500,000 ohms. The bond between the membrane and AC is acceptable if disbonding occurs within the AC layer rather than at the AC-membrane interface.

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The bend test is performed first since experience has indicated that a membrane that fails the bend test will usually fail the tension test. The bend test, performed under the restrictions of the Pliability Section of ASTM Designation D-146, consists of bending test specimens at -5°F around a one inch mandrel after the specimens have been conditioned in a 140°F oven for 30 days.

In general, initial field and laboratory observations of membrane characteristics are in reasonable agreement. Experience to date has indicated that specifications covering construction procedures and field evaluation of the completed installation must be carefully prepared and then followed very closely.

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"CORROSION TESTING OF BRIDGE DECKS"

That many bridge decks are exhibiting premature signs of distess and failure, and that this distress is primarily due to the increased use of deicing salts are well documented and widely accepted facts. NCHRP Synthesis No. 4 expresses concern for 200,000 bridge decks in the United States. Neither money nor personnel are available to completely evaluate the corrosion condition of each of these structures. Present techniques to determine the most suitable method of repair and/or preservation must be streamlined. The object of this study was find the means to obtain such necessary technical information with a minimum of effort and expense. Effort was expended to evaluate corrosion investigation techniques rather than specific concrete characteristics.

Corrosion investigations were conducted on 22 bridges with data accumulated by chloride analysis, electrical potential measurements, chaining to outline areas of concrete delamination, and pachometer measurements of concrete cover over the reinforcing steel.

Test data confirmed previously determined relationships concerning chloride content at the steel level, corrosive potentials and concrete delaminations. Increasing chloride contents do not necessarily result in increasing corrosive potentials or concrete delaminations. Such increases are associated with continuing corrosion of the steel since, once corrosion begins, it becomes more extensive as time passes. The only salt content of importance is that minimum amount which destroys the passivity of the steel. At this point, corrosion begins and the rate is controlled by other factors. An increase in salt content over the amount necessary to destroy passivity is not required to maintain active corrosion, nor will such an increase affect the corrosion rate.

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Data were gathered to compare the chloride contents of identical concrete samples obtained by coring and by drilling. A statistical analysis of these data indicated that the accuracy of the resulting chloride contents were about equal for the two sampling methods.

Data accumulated in this study concerning potentials and concrete condition seem to confirm relationships established by prior research. The average maximum potentials for large and small delaminations were -0.453 v and -0.385 v CSE, respectively, and the average of all potentials for sound (not delaminated) concrete was -0.180 v CSE. Although these data cannot be used to establish a passive steel potential, they again confirm that potentials more negative than -0.35 v CSE are a very reliable indicator of active corrosion.

A comparison was made between complete bridge deck potential surveys and a random selection method. The random method consisted of obtaining a minimum of 30 measurements at approximately 4 ft. spacing in the curb area of lowest elevation. The resulting data indicate that the random survey, while not perfect and having limitations, appears to be a satisfactory and economical procedure for evaluation of the corrosion activity of bridge decks where a rapid survey of numerous structures is required. This method is particularly useful where several bridges in a given area have received similar salt applications.

Complete deck surveys were taken before and after delaminated concrete was removed and replaced. This type of repair results in an initial reduction in corrosive potentials of approximately 50%. Indications are that such repairs do not cause an end to corrosion or prevent the beginning of corrosion at other points in the deck.

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"LABORATORY CORROSION TESTS OF GALVANIZED STEEL IN CONCRETE"

Galvanized steel bars are being used in reinforced concrete structures to prevent or postpone corrosion of the steel in the presence of salt. Although a number of reports have been written on this subject, a consistent indication of a resulting significant benefit is lacking. The purpose of this study was to evaluate under more controlled conditions the protection that zinc provides for steel embedded in salt-contaminated concrete.

Test parameters evaluated included steam and water curing; 5, 6, and 7 sacks per cu yd cement factors; black and galvanized reinforcing steel; and partial immersion of corrosion test blocks in a saturated sodium chloride solution and in local tap water. Ninety corrosion test blocks, cast from eleven batches of concrete, were fabricated and tested as described previously. Prior to galvanizing, the reinforcing steel specimens were sandblasted and weighed. Individual coating thickness was calculated from the difference between the bare and coated weights. The calculated zinc coating weights varied from 2.60 to 4.65 oz per sq ft, with an average of about 3 oz per sq ft. Absorption tests were performed on specimens which were cast from each of the eleven concrete batches.

Electrical potential measurements indicated that the time to corrosion was about equal for both the galvanized and black steel specimens. Regardless of concrete quality or curing method, thicker coatings of zinc resulted in a shorter time to corrosion-caused concrete cracking. In addition, galvanized specimens in high quality concrete had a shorter time to corrosion-caused concrete cracking than did the black steel specimens. It was reasoned that higher quality concrete had less capacity to absorb corrosion products, therefore, stresses sufficient to

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rupture the concrete were reached sooner than they were reached in the more absorbent concrete. It was not possible to determine potential ranges that would clearly indicate an active (corroding) or passive (noncorroding) condition of the zinc in concrete.

It appears that zinc behaves similarly to steel in salt contaminated concrete; it corrodes and causes concrete cracking.

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RESEARCH IMPLEMENTATION

In general, the research studies described in these twelve reports have been a "pioneering" sort. Very little prior work existed in this particular subject area. A good deal of effort has been expended in "trial and error" and in just learning about steel corrosion in concrete. Much additional effort has been required to develop standard test procedures and to verify that such procedures could be duplicated.

The list of original testing and evaluation procedures developed by this project includes the following:

1. Standard procedure for laboratory corrosion testing.

2. Standard procedures for field evaluation of bridge deck corrosion activity.

3. Standard procedure for an abbreviated random corrosion survey of bridge decks. This procedure was utilized in a 1975 survey in which over 1000 bridge decks were evaluated.

4. Standard procedures for field and laboratory testing and evaluation of waterproof membranes.

It is recommended that field evaluation be included as part of the routine procedure for all future membrane installations.

Mix design information contained in these reports has been made available to the designers of reinforced concrete items. In addition, this research is the basis for Section 6-14 "Corrosion Protection for Concrete", Bridge Planning and Design Manual, which lists various design alternatives for structures that will be subjected to a chloride environment. Depending on the

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chloride content of the water or soil, the required actions can include increasing the cement factor, applying a protective coating to concrete surfaces, and increasing the minimum cover for reinforcing steel.

As a result of this and another associated project, Caltrans is discontinuing the use of deicing salts on bridge decks in valley areas. A noncorrosive deicer and special deck surfacing are now being considered as emergency measures to prevent the formation of frost on bridge decks and/or to provide skid resistance should frost occur.

Research from this project provided much of the information presented in a training film on corrosion detection. This film, prepared for FHWA, is being used to aid in the training of city, county, and state personnel throughout the United States in the techniques used to detect steel corrosion in reinforced concrete bridge structures.

Procedures developed during this project concerning the electrical evaluation of bridge deck membranes and the use of half-cell potential readings to detect the corrosion of steel in concrete are being used by an ASTM subcommittee preparing standard test methods.

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