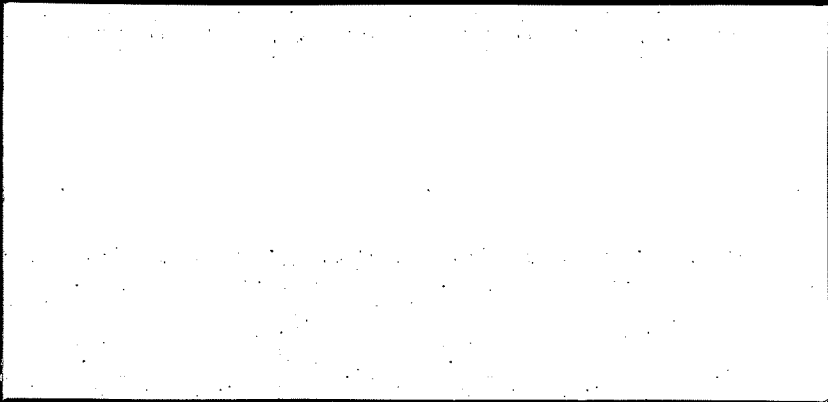


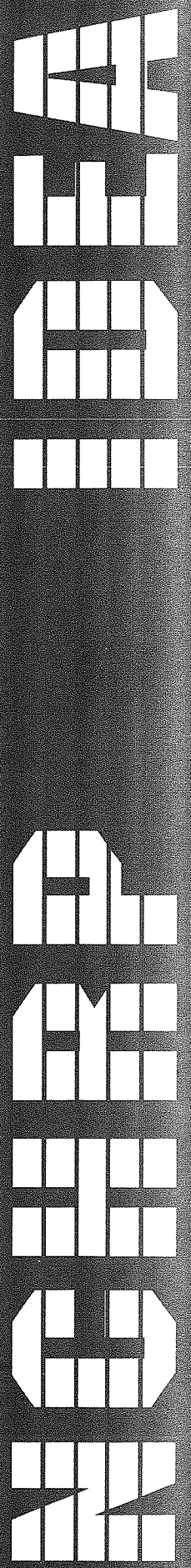
TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

IDEA *Innovations Deserving
Exploratory Analysis Project*

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM



Report of Investigation



IDEA PROJECT FINAL REPORT
Contract NCHRP-93-ID009

IDEA Program
Transportation Research Board
National Research Council

May 31, 1995

CORROSION-RESISTANT
STEEL REINFORCING BARS

David Darwin
University of Kansas

**INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA)
PROGRAMS
MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)**

This NCHRP-IDEA investigation was completed as part of the National Cooperative Highway Research Program (NCHRP). The NCHRP-IDEA program is one of the four IDEA programs managed by the Transportation Research Board (TRB) to foster innovations in highway and intermodal surface transportation systems. The other three IDEA program areas are Transit-IDEA, which focuses on products and results for transit practice, in support of the Transit Cooperative Research Program (TCRP), Safety-IDEA, which focuses on motor carrier safety practice, in support of the Federal Motor Carrier Safety Administration and Federal Railroad Administration, and High Speed Rail-IDEA (HSR), which focuses on products and results for high speed rail practice, in support of the Federal Railroad Administration. The four IDEA program areas are integrated to promote the development and testing of nontraditional and innovative concepts, methods, and technologies for surface transportation systems.

For information on the IDEA Program contact IDEA Program, Transportation Research Board, 500 5th Street, N.W., Washington, D.C. 20001 (phone: 202/334-1461, fax: 202/334-3471, <http://www.nationalacademies.org/trb/idea>)

The project that is the subject of this contractor-authored report was a part of the Innovations Deserving Exploratory Analysis (IDEA) Programs, which are managed by the Transportation Research Board (TRB) with the approval of the Governing Board of the National Research Council. The members of the oversight committee that monitored the project and reviewed the report were chosen for their special competencies and with regard for appropriate balance. The views expressed in this report are those of the contractor who conducted the investigation documented in this report and do not necessarily reflect those of the Transportation Research Board, the National Research Council, or the sponsors of the IDEA Programs. This document has not been edited by TRB.

The Transportation Research Board of the National Academies, the National Research Council, and the organizations that sponsor the IDEA Programs do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of the investigation.

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	1
IDEA PRODUCT	2
CONCEPT AND INNOVATION	2
INVESTIGATION	2
MATERIALS	3
Reinforcing Steel	3
Mortar and Concrete	5
LABORATORY INVESTIGATION	5
Stage 1 - Rapid Corrosion Potential and Time-to-Corrosion Tests	5
Stage 2 - Bench Scale Time-to-Corrosion Tests	7
Stage 3 - Evaluation of Effect of Deicer Type and Concentration	8
Stage 4 - Mechanical Properties	8
RESULTS	8
Stage 1 - Rapid Corrosion Potential and Time-to-Corrosion Tests	8
Stage 2 - Bench Scale Time-to-Corrosion Tests	11
Stage 3 - Evaluation of Effect of Deicer Type and Concentration	16
Stage 4 - Mechanical Properties	16
Summary of Findings	16
PLANS FOR IMPLEMENTATION	19
CONCLUSIONS	20
INVESTIGATOR PROFILE	20
REFERENCES	20
NOTATION	21

ACKNOWLEDGEMENTS

This study was supported by the National Highway Research Program - Innovations Deserving Exploratory Analysis under Contract Number NCHRP-93-ID009. Major monetary and material support was provided for the project by Florida Steel Corporation. In addition, corrosion inhibiting admixtures were provided by Master Builders, Inc. and W. R. Grace & Co. Calcium magnesium acetate for use in this study was provided by Cryotech Deicing Technology.

In addition to the principal investigator, the major participants in this study were Professor Carl E. Locke, Jr. and graduate students Matthew R. Senecal, Shawn M. Schwensen, and Jeffrey L. Smith.

EXECUTIVE SUMMARY

The corrosion of reinforcing steel in highway structures results in maintenance and replacement costs in the United States that are measured in billions of dollars. These costs would be greatly reduced and the durability and design life of reinforced concrete structures greatly enhanced if the corrosion resistance of reinforcing steel were improved. This study involves the evaluation of a concrete reinforcing steel which has shown superior corrosion-resistant properties. Previous evaluations have concentrated on the corrosion resistance of the steel in the atmosphere, which can be quite different than obtained for steel in contact with concrete. Emphasis in this study is placed on the corrosion resistance of the steel in concrete structures.

The new steel differs from steel used in standard U.S. practice in a number of ways. Additional alloying elements (copper, chromium, and phosphorus) are used, along with a special heat treatment, to provide the corrosion-resistant properties of the steel. The bars possess lower carbon content than is usual, and the phosphorous content exceeds that allowed in ASTM specifications. The bars are quenched and tempered immediately following the rolling operation, a step that places the exterior of the bars in compression. The apparent corrosion-resisting mechanisms include the formation of a corrosion-retarding layer of copper chloride-copper hydroxide at the steel surface in the presence of chloride, the formation of phosphorous oxides, which serve as corrosion inhibitors, the formation of iron-chromium oxide at the steel surface, which is a poor conductor and, thus, reduces the corrosion rate, and the reduction of microfractures in the surface from the rolling operation due to the quenching and tempering process. The corrosion products that form are much denser than for normal reinforcing steel, which further reduces the availability of oxygen and water at the steel surface. The reduced microfracturing lowers the surface area available for corrosion.

The study is carried out in four overlapping stages. Stages 1 and 3 are dedicated to understanding the corrosion protection mechanisms and the degree of corrosion protection when the steel is subjected to different chloride concentrations and different deicing chemicals. Stage 2 involves the evaluation and comparison of the new reinforcement to standard reinforcing steel using accepted time-to-corrosion tests. Stage 4 consists of a determination of the mechanical properties of the new steel, as affected by the alloying process. The study involves the evaluation of four types of steel, representing combinations of alloying elements and heat treatment. The steels include two conventional steels, one hot-rolled and one subjected to heat treatment immediately following the hot-rolling operation, and two forms of corrosion-resistant steel, one hot-rolled and one heat-treated.

The experimental results and analyses demonstrate that the microalloying procedure improves the corrosion resistance of steel reinforcing bars cast in concrete and subjected to deicing chemicals. The resulting corrosion rate is approximately one-half of the corrosion rate exhibited by conventional reinforcing bars. The use of the quenching and tempering heat treatment following hot rolling appears to provide some additional corrosion resistance, when used in conjunction with the microalloying procedure. The heat treatment produces a reinforcing steel with higher yield and tensile strengths. A phosphorous content in excess of that allowed under current ASTM requirements does not cause the corrosion-resistant steel in this study to be brittle. The tests indicate that the new reinforcing steel should not be combined with conventional reinforcement in reinforced concrete structures. The new steel performs well when used in conjunction with an epoxy coating and offers the potential of economically providing a measurable improvement in the corrosion performance of reinforced concrete structures subjected to chlorides and deicing chemicals.

Implementation of the new reinforcing steel will require additional corrosion tests to fully document the corrosion-resistant properties of the reinforcement, the development of standard specifications for the material, and the execution of demonstration projects in which the new reinforcing steel is applied in practice. Special attention should be given to using the new steel in conjunction with epoxy coating.

IDEA PRODUCT

The corrosion of reinforcing steel in highway structures in coastal areas and where deicing salts are used results in maintenance and replacement costs in the United States that are measured in billions of dollars. This study involves the evaluation of a concrete reinforcing steel which has exhibited superior corrosion resistant properties. The effort is based on work by a steel company in India (1, 2) that provides evidence that using copper, chromium, and phosphorous as microalloying elements and heat treating the steel following the rolling process enhances corrosion resistance. The key goal of the study is to evaluate the degree of the enhancement in corrosion resistance achieved by these techniques under realistic conditions. If the added corrosion resistance of the new steel is demonstrated, its use will greatly enhance the durability and life expectancy of transportation structures.

CONCEPT AND INNOVATION

The new reinforcing steel differs from steel used in standard U.S. practice in a number of ways. Additional alloying elements, copper, chromium, and phosphorous, are used along with a special heat treatment to provide the corrosion-resistant properties of the steel (3). The bars possess lower carbon content than is usual in U.S. practice, and the phosphorous content exceeds that allowed in ASTM specifications (4, 5). The bars are quenched and tempered immediately following the rolling operation, a step that places the exterior of the bars in compression. The apparent corrosion-resisting mechanisms include the formation of a corrosion retarding layer of copper chloride-copper hydroxide at the steel surface in the presence of chlorides, the formation of phosphorous oxides, which serve as corrosion inhibitors, the formation of iron-chromium oxide at the steel surface, which is a poor conductor, and thus reduces the corrosion rate (1, 2), and the reduction of microfractures in the surface from the rolling operation due to the quenching and tempering process. The corrosion products that form are much denser than for normal reinforcing steel, which further reduces the availability of oxygen and water at the steel surface. The reduced microfracturing further reduces the surface area available for corrosion.

Prior to the current study, the procedures used to evaluate the steel have concentrated primarily on the corrosion resistance of bars not in contact with concrete. Only one series of accelerated corrosion tests were used to study bars in contact with concrete; and these tests, involving total submersion in salt water of concrete blocks containing individual reinforcing bars, do not present a full picture of the corrosion process of steel in concrete and are not accepted in U.S. practice.

The specific technical issue addressed in this study does not involve the ability of the steel to be more corrosion resistant in the atmosphere, which seems to have been amply established in earlier studies, but, rather, the evaluation of its corrosion resistance when embedded in concrete, where the environment is significantly different. The distinction is important since there are many materials that exhibit superior corrosion resistance in the atmosphere but perform poorly in concrete.

Reinforcing steel will not corrode in uncontaminated portland cement concrete due to the high pH environment and the calcium hydroxide that precipitates at the steel surface (6). The pore solution in portland cement concrete has a pH of about 13.8 and contains a mixture of potassium and sodium hydroxides. Steel in this environment is passive and remains in a noncorrosive condition unless contaminants like chloride ions or carbon dioxide intrude. To evaluate the new steel for practical application requires testing in an environment in which the steel is in contact with hydrated cement paste (in mortar or concrete) and subjected to sufficient chlorides so that macrocorrosion cells can develop.

Two general categories of test specimens have been developed to resolve the key technical issues. Small test specimens, with low cover over the reinforcing steel, are used to obtain a rapid measure of the corrosion of the reinforcing steel, and larger test specimens, with realistic concrete covers, are used to evaluate the practical performance of the reinforcing steel over extended periods of time. The latter test specimens are the only types generally accepted in U.S. practice.

INVESTIGATION

The objective of this investigation is to evaluate a new concrete reinforcing steel that has shown superior corrosion-resistant properties in previous tests (1, 2). The project is designed to determine the technical feasibility of using the corrosion-resistant reinforcing bars in highway structures, with an understanding of both the specific advantages and the limitations of the new material.

The tests used in India (1, 2) to demonstrate the corrosion resistance of the new steel in concrete involved alternate wetting and drying of concrete blocks containing the steel. While the new steel performed much better than regular reinforcement under extreme chloride exposure conditions, the tests did not present a full picture of the corrosion process in

concrete because they evaluated corrosion of individual reinforcing bars. Obtaining a true measure of the corrosion resistance of the steel requires the evaluation of the corrosion of bars in an active macrocell.

A macrocell in reinforced concrete is created when a region of the reinforcing steel is in a corrosive condition and an adjacent region of the steel is in a noncorrosive condition. Macrocells occur when chloride intrudes and changes the condition of a region of the steel while adjacent regions are not contacted by the chlorides. The effect of chloride ions on passive steel is to shift the corrosion potential several hundred millivolts in the negative direction. Therefore, steel in the passive condition is several hundred millivolts different than the adjacent steel, which sets up a "galvanic-like" corrosion cell. This cell is called a macrocell. A corrosion current results from this potential difference, which is why steel corrodes to such a great extent in chloride-contaminated concrete. Thus, to gain a true measure of the corrosion resistance of the new steel, test procedures must provide realistic models of reinforced concrete structures and allow the formation of macrocells. The models used most often are the Southern Exposure (or SE) test to represent corrosion conditions in uncracked concrete and the cracked beam test to represent conditions in which a portion of the steel is directly exposed to the atmosphere (7-9). These tests are described later in the report.

The original corrosion study (1, 2) demonstrated that the corrosion resistance of the new reinforcing steel in the atmosphere is enhanced by quenching and tempering the reinforcing bars following the rolling operation. This improvement may be the result of the residual compressive stresses that exist on the surface of the heat-treated bars, a kind of reverse stress corrosion process. Therefore, both 1) quenched and tempered and 2) hot-rolled reinforcement are evaluated to determine if the advantages observed for bars in the atmosphere are also observed for bars cast in concrete.

The use of combinations of corrosion protection techniques, such as the addition of corrosion inhibitors to the concrete in conjunction with the use of epoxy-coated steel, is becoming more and more common (for example, at the new Denver airport). These combinations are often used without a prior evaluation of the effects of using two processes together. Since the corrosion protection provided by the new reinforcing steel involves the formation of protective corrosion products that are different than those formed on normal reinforcing steel (2), the new steel is also evaluated in conjunction with both corrosion inhibitors and epoxy coating.

During earlier research at the University of Kansas (10), the effects of deicer type and concentration on the corrosion potential of reinforcing bars cast in concrete were studied. Differences were observed for sodium chloride, calcium chloride, and calcium magnesium acetate. A similar but more detailed evaluation is carried out in this study using the same three deicing chemicals.

Finally, the phosphorous content of the new steel exceeds that currently allowed in U.S. practice (4, 5). Upper limits are placed on phosphorous content because it can reduce the yield strength and increase the brittleness of steel. These drawbacks can be overcome by the addition of other alloying elements (which can substantially increase the price of the steel) or by quenching and tempering the steel using the Thermex/Tempcore process (which can, in fact, reduce the cost of steel because alloying requirements are reduced). Because of these effects, both Thermex-treated and hot-rolled bars manufactured from the new steel are evaluated based on mechanical properties.

The study was carried out in four overlapping stages. Stages 1 and 3 were dedicated to understanding of the corrosion protection mechanisms and the degree of corrosion protection when subjected to different chloride concentrations and different deicing chemicals. Stage 2 involved the evaluation and comparison of the new reinforcement to standard reinforcing steel using accepted time-to-corrosion tests. Stage 4 consisted of an evaluation of the mechanical properties of the new steel as effected by the alloying process.

MATERIALS

Reinforcing Steel

The reinforcing steel evaluated in this study (produced by Florida Steel Corporation) consisted of corrosion-resistant steel (CRS) bars, rolled from one experimental heat of steel, and conventional steel, rolled from two heats. Both heat-treated (Thermex, T) and nonheat-treated (hot-rolled, H) bars were produced for each material. Additional conventional hot-rolled steel (produced by Chaparral Steel Company) was used for comparison with CRS bars with an epoxy coating. All bars had a nominal diameter of 16 mm (ASTM designation: No. 5). The CRS steel is designated CRST or CRSH, and the conventional steel is designated T or H. The chemical analyses of the steels are presented in Table 1. Table 1 also shows the chemical requirements, as recommended in the original study (1, 3). The CRSH/CRST steel meets most of the recommended requirements (1, 3). It does, however, have a higher carbon content (0.20 percent versus a maximum of 0.18 percent) and a higher carbon equivalent (0.53 percent versus a range of 0.30 to 0.45 percent) than recommended. The phosphorous content, 0.08 percent, is well below the recommended maximum of 0.12 percent. The first listed heat of H/T steel was used for the specimens in Stages 1 and 3 of this study. The second listed heat of H/T steel was used for

TABLE 1 Chemical Composition of 16 mm (No. 5) Steel Reinforcing Bars, in percent

Steel Type	Heat ID No.	C	Mn	S	V	Si	Ni	Sn	Mo	P	Cr	Cu	P + Cr + Cu	C.E.*
H, T**	K5-5546	0.32	0.72	0.044	0.000	0.22	0.14	0.011	0.018	0.026	0.14	0.34	0.51	0.50
H, T**	K4-3064	0.36	0.67	0.027	0.002	0.17	0.09	0.011	0.016	0.017	0.12	0.30	0.44	0.52
H***	2-0977	0.43	0.75	0.017	0.000	0.30	0.09	0.000	0.019	0.018	0.11	0.23	0.35	0.60
CRSH, CRST**	K3-1725	0.20	0.76	0.032	0.003	0.23	0.11	0.011	0.011	0.080	0.53	0.44	1.05	0.53
CRS	Recommended (I-3)	0.18 max.	0.85 max.	0.035 max.		0.45 max.				0.120 max.	0.80 max.	0.50 max.	0.90 min.	0.30/0.45

*Carbon Equivalent = $C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo)/5 + V/0.5$

**Produced by Florida Steel Corporation

***Produced by Chaparral Steel Company

Stage 2. The fusion-bonded epoxy coatings (produced by Morton Powder Coatings, Inc. for the Florida Steel bars and by O'Brien Powder Products, Inc. for the Chaparral Steel bars) were applied in accordance with the requirements of ASTM A 775 (11).

Mortar and Concrete

The mortar and concrete used to fabricate test specimens were made with Type I portland cement and a water/cement ratio of 0.5. The mortar had a sand-cement ratio of 2.0 and is made with ASTM C 778 (12) graded Ottawa sand and deionized water. The concrete was air-entrained, with a 6 percent air content, and was made using river sand (bulk specific gravity $ssd = 2.62$), 19 mm ($3/4$ in.) crushed limestone coarse aggregate (bulk specific gravity $ssd = 2.54$), and tap water (C:S:CA = 1:2.61:2.43).

The effects of corrosion inhibiting admixtures were evaluated using commercial inorganic (calcium nitrite, W. R. Grace DCI-S) and organic (Master Builders Rheocrete 222) corrosion inhibitors, used at dosage rates of 19.8 l/m^3 (4 gal/yd³) and 5 l/m^3 (1 gal/yd³), respectively.

LABORATORY INVESTIGATION

Stage 1 - Rapid Corrosion Potential and Time-to-Corrosion Tests

The tests used for rapid evaluation of corrosion are based on earlier work at the University of Kansas under the SHRP program (10, 13). The tests allow very rapid evaluation of both the corrosion potential and the formation of a corrosion macrocell for reinforcement. The basic test specimen for these tests (Figure 1) consists of a length of reinforcing bar embedded in a cylinder of mortar. The contact surface between the mortar and the bar simulates the contact obtained between concrete and reinforcing bars in actual structures due to the use of both a realistic water-cement ratio (slightly higher than normal to provide for the earlier initiation of corrosion) and a realistic sand-cement ratio.

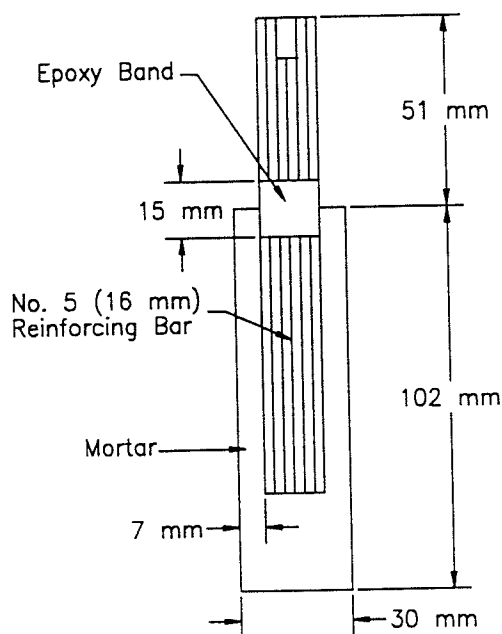


FIGURE 1 Cross Section of Test Specimen Used for Rapid Corrosion Potential and Macrocell Tests

The corrosion potential test (Figure 2) requires two plastic containers. The test specimen is placed in a 5 liter contain-

er along with crushed mortar fill and a simulated pore solution containing a preselected concentration of sodium chloride (NaCl). A standard Calomel reference electrode is placed in a separate container along with a saturated potassium chloride solution. The two containers are connected by a salt bridge, and the potential (voltage) of the steel with respect to the Calomel electrode is measured at selected time intervals using a digital voltmeter. This voltage is called the corrosion potential of the steel.

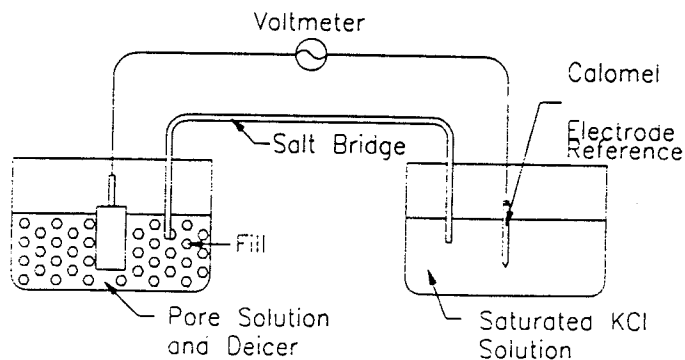


FIGURE 2 Schematic of Corrosion Potential Test

The mortar fill consists of the same mixture as used in the test specimen. The fill is used primarily to serve as a buffer and to help simulate the relative amount of cementitious material that exists in an actual structure. The simulated pore solution (17.84 g of sodium hydroxide and 18.81 g potassium hydroxide per liter of solution) represents the liquid in the saturated pores and capillaries in concrete (14, 15). Together with the mortar fill, it helps establish a realistic environment to measure the progress of corrosion of reinforcing steel. The salt bridge allows for the completion of the corrosion cell at the time that the corrosion potential is measured.

To obtain a rapid measure of the degree of corrosion that occurs through the formation of a macrocell, the corrosion potential test is modified, as shown in Figure 3. The container with the Calomel electrode is replaced by another container with two standard specimens surrounded by mortar fill and immersed in simulated pore solution (with no chlorides added) in a second container. The test specimen in the pore solution containing sodium chloride (anode) is electrically connected through a single 10 ohm resistor to the two specimens in the simulated pore solution (cathode). The macrocell test specimen is completed by a salt bridge that connects the liquid in the two containers. Air (scrubbed to remove CO₂) is bubbled into the liquid surrounding the cathode to insure an adequate supply of oxygen. The air causes some evaporation, which is countered by adding deionized water to the container to maintain a constant volume of the solution. The corrosion current and the rate of corrosion can be determined by measuring the voltage drop across the resistor. For this study, 0.4, 1.0, 1.6 and 6.04 molal (m) ion solutions of sodium chloride are used. The latter solution is equivalent to a 15 percent concentration [molal concentration = moles of solute/kg of solvent; percentage concentration = (weight of solute/weight of solution) x 100 percent]. One to three replications were used for each combination of test variables.

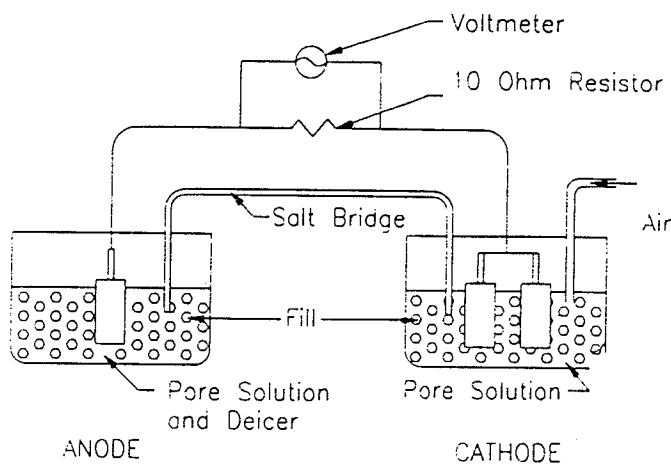


FIGURE 3 Schematic of Macrocell Test

Stage 2 - Bench Scale Time-to-Corrosion Tests

Two widely accepted long-term tests are used to determine the rate of corrosion of reinforcing steel in both uncracked and cracked concrete. The first test specimen, the Southern Exposure or SE specimen (8), consists of a small slab containing two mats of reinforcing steel (Figure 4). The concrete is wet cured for three days and then air cured until the tests begin at 28 days. The top mat consists of two bars; the bottom mat consists of four bars. The mats are electrically connected across a 10 ohm resistor. A dam is placed around the edge of the top surface, and the sides of the concrete are sealed with epoxy. A 15 percent sodium chloride solution is placed inside the dam, allowing the chlorides to penetrate into the concrete. The slabs are subjected to a 7-day alternate ponding and drying regime, with ponding at 22°C (72°F) for four days and drying at 38°C (100°F) for three days. The test provides a very severe corrosion environment and is generally believed to simulate 15-20 years of exposure for marine structures and 30-40 years of exposure for bridges within a 48 week period (6). No effort is made to control crack depth or width as the test proceeds.

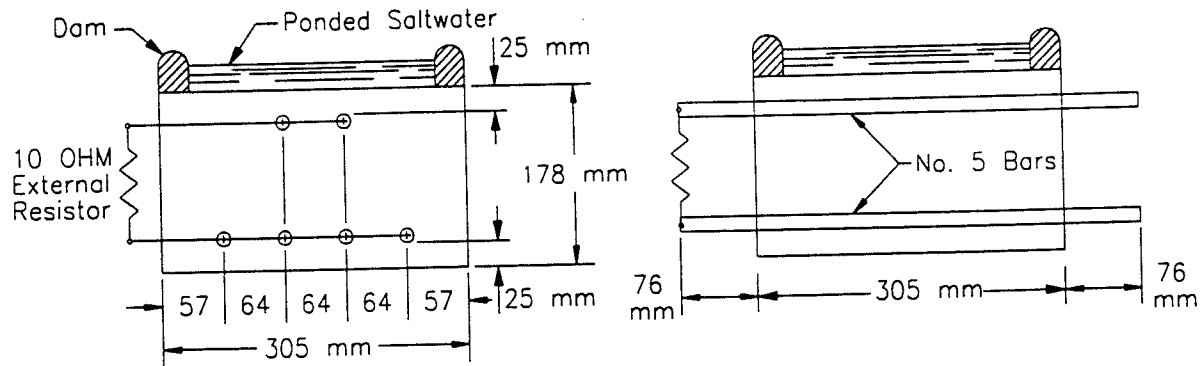


FIGURE 4 Southern Exposure Test Specimen

The second test specimen, the cracked-beam specimen, shown in Figure 5, is half the width of the SE specimen and has one bar on top and two bars on the bottom. After three days of wet curing, the beam is cracked to provide a crack width of approximately 0.33 mm (0.012 in.) at the level of the top bar. A dam is placed around the specimen in a manner similar to that used for the SE specimen. Like the SE specimen, the cracked-beam specimen is subjected to cycles of wetting and drying with a 15 percent sodium chloride solution beginning 28 days after casting. Also, like the SE tests, the cracked-beam tests are carried out for 48 weeks. No effort is made to control crack depth or width as the test proceeds.

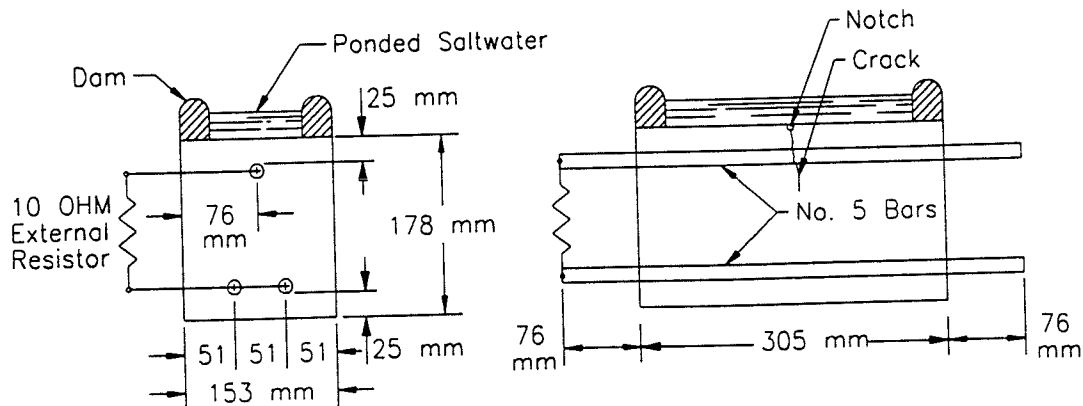


FIGURE 5 Cracked Beam Test Specimen

In this stage, the four steels are evaluated using the Southern Exposure and cracked beam specimens. In addition, combinations of the H and CRST steels are evaluated in the SE and cracked beam specimens using the H steel in the upper

mat and the CRST steel in the lower mat and, alternately, the CRST steel in the upper mat and the H steel in the lower mat. The CRSH and CRST steels are used in conjunction with the organic and inorganic corrosion inhibitors in both the SE and cracked beam specimens. Finally, epoxy-coated H, CRSH, and CRST bars are evaluated using SE specimens. For these specimens, the upper mat consists of two epoxy-coated bars, while the lower mat consists of four uncoated bars. For each of the bars in the upper mat, the epoxy is penetrated at four evenly spaced locations using a 3 mm ($1/8$ in.) diameter drill. The drill penetrates only far enough to remove the epoxy coating. The bars are positioned in the SE specimens so that the holes face in the horizontal direction.

Three replications are used for each combination of variables.

To determine the chloride content corresponding to the initiation of corrosion in the SE specimens, samples of concrete are collected and analyzed in accordance with the SHRP "Standard Test Method for Chloride Content in Concrete Using the Specific Ion Probe" (16). Samples are obtained using a 6.5 mm ($1/4$ in.) diameter drill bit. The upper edge of the drill is placed 25 mm (1 in.) below the upper surface of the specimen to collect material just below the level of the upper surface of the reinforcing steel. The holes are drilled from a side that is parallel with the bars. Concrete is sampled at a depth of 25 to 50 mm (1 to 2 in.) at two locations, about 50 mm (3 in.) from opposite edges of the side. The material from the two holes is combined and the composite sample is analyzed.

Stage 3 - Evaluation of Effect of Deicer Type and Concentration

In this stage of the study, the effects of different deicers on the initiation of corrosion for the four types of steel are compared by replacing the sodium chloride solutions used in Stage 1 with 0.4, 1.6 and 6.04 molal ion solutions of calcium chloride (CaCl_2) and calcium magnesium acetate (CMA) (3 moles calcium acetate to 7 moles of magnesium acetate). The tests involve two replications for each combination of test variables.

Stage 4 - Mechanical Properties

The use of higher phosphorous contents in reinforcing steels is generally associated with a reduction in the tensile strength and ductility of steel. The yield and tensile strengths, along with the elongation and bending properties of the new steels are compared to industry standards (4, 5). Of specific interest is the comparison of the strengths of the CRST and CRSH bars, since decreased tensile strength and ductility can be overcome through the use of the Thermex process or through the use of additional alloying elements.

RESULTS

The principal results of this study are conveyed based on the data from the macrocells in terms of corrosion rates versus time. The corrosion rates, calculated using Faraday's Law based on the measured corrosion on currents (17), are expressed in micrometers per year ($25.4 \mu\text{m} = 0.001$ in.). Time is expressed in days for the rapid macrocell tests and in weeks for the bench scale tests.

Stage 1 - Rapid Corrosion Potential and Time-to-Corrosion Tests

An analysis of the corrosion potential tests shows little difference between the regular hot-rolled (H), regular Thermex (T), corrosion-resistant hot-rolled (CRSH) and the corrosion-resistant Thermex (CRST) steels. There are, however, significant differences in the performance of the steels in the macrocell tests. These results are illustrated in Figures 6, 7, 8, and 9 for specimens subjected to 0.4, 1.0, 1.6, and 6.04 (15 percent) molal ion solutions of sodium chloride, respectively. The figures show the average corrosion rates for the number of specimens indicated (1, 2, or 3). Specimens that did not exhibit a corrosion rate of at least $1 \mu\text{m}/\text{yr}$ at some time during the 100 days during which the tests were carried out are not used to develop the average results shown.

Overall, the CRSH and CRST steels exhibited measurably lower corrosion rates than the H and T steels, with the CRST steel, on average, exhibiting a lower corrosion rate than the CRSH steel. For the 0.4 and 1.0 m ion NaCl solutions (Figures 6 and 7), the new steels exhibited corrosion rates on the order of one-half of the corrosion rate exhibited by the two conventional steels. For the 1.6 m ion concentration (Figure 8), the CRST steel exhibited very low corrosion (less than $1 \mu\text{m}/\text{yr}$ for most of the test), which is significantly less than that exhibited by the CRSH steel (about $3 \mu\text{m}/\text{yr}$ at the end of the test) and the H and T steels (in excess of $4 \mu\text{m}/\text{yr}$ for most of the test). For the 6.04 m ion solution

(Figure 9), the CRSH and T steels exhibited the lowest corrosion rate (about 3 $\mu\text{m}/\text{yr}$), followed by the CRST steel (about 4 $\mu\text{m}/\text{yr}$) and H steel (about 6 $\mu\text{m}/\text{yr}$). The relatively high corrosion rate exhibited by the CRST steel is the result of a high corrosion rate exhibited by one of the three specimens included in the average. There is a possibility that the test setup malfunctioned in some way. However, the test result is included for completeness and to insure no intentional bias in the results.

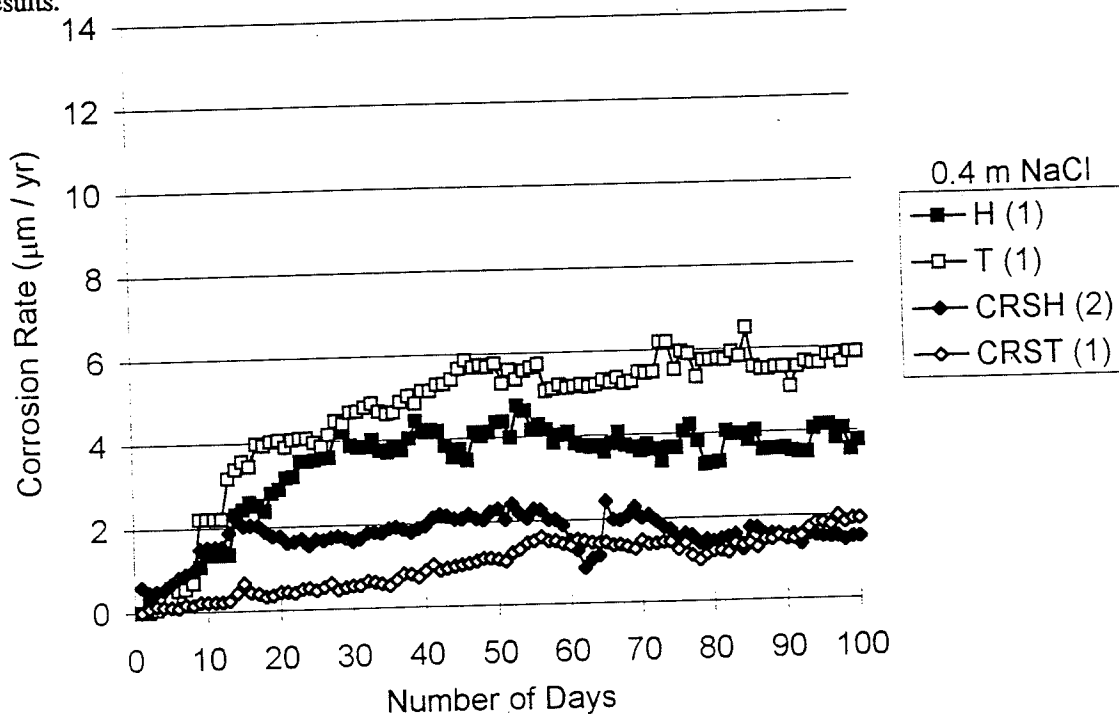


FIGURE 6 Corrosion Rate Versus Time for Macrocell Tests, 0.4 Molal Ion Solution of Sodium Chloride, Comparing H, T, CRSH and CRST Steels (1 μm = 0.025 in.)

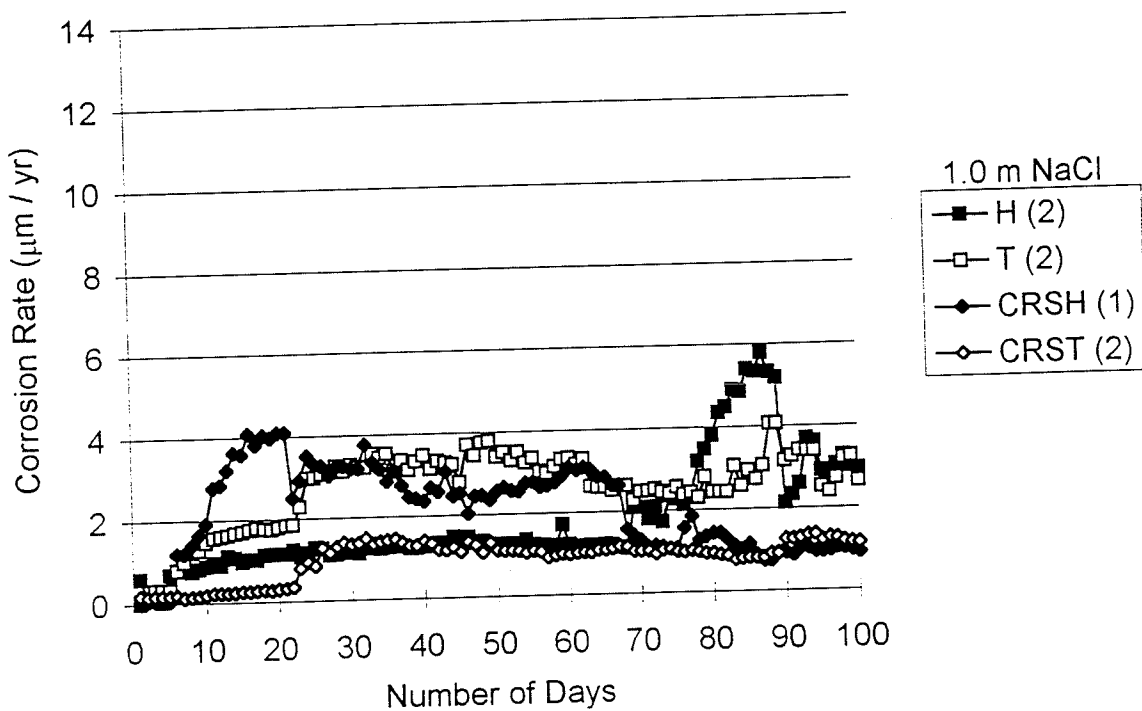


FIGURE 7 Corrosion Rate Versus Time for Macrocell Tests, 1.0 Molal Ion Solution of Sodium Chloride, Comparing H, T, CRSH and CRST Steels (1 μm = 0.025 in.)

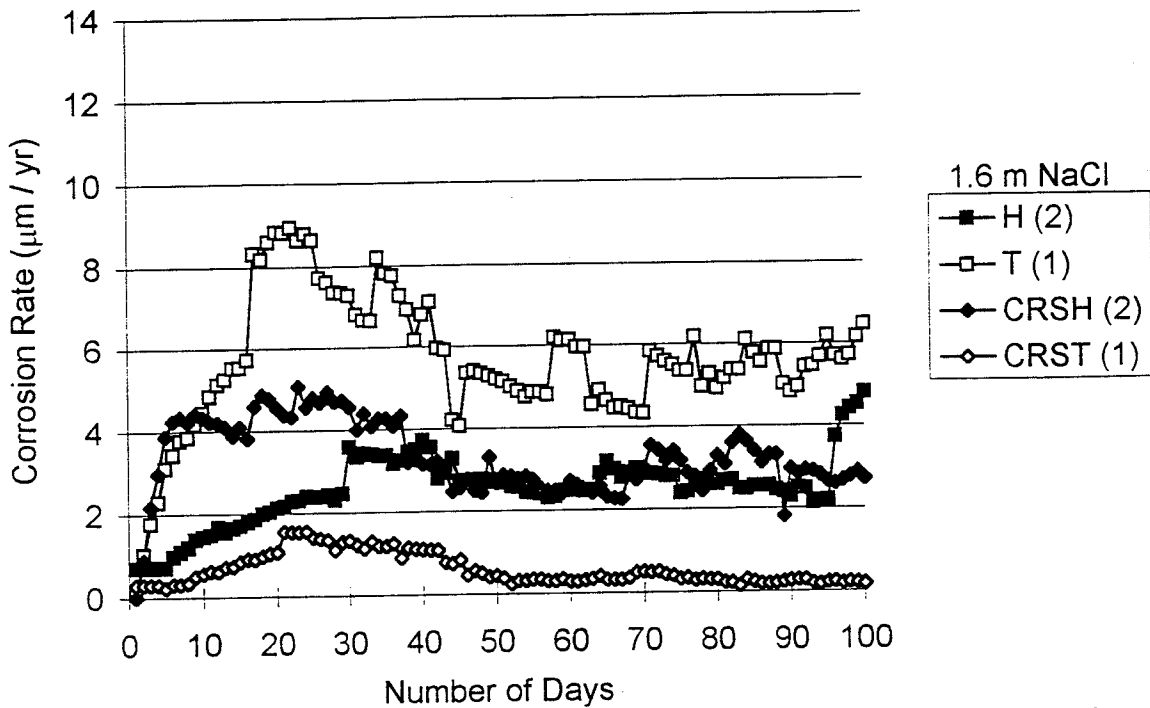


FIGURE 8 Corrosion Rate Versus Time for Macrocell Tests, 1.6 Molal Ion Solution of Sodium Chloride, Comparing H, T, CRSH and CRST Steels (1 μm = 0.025 in.)

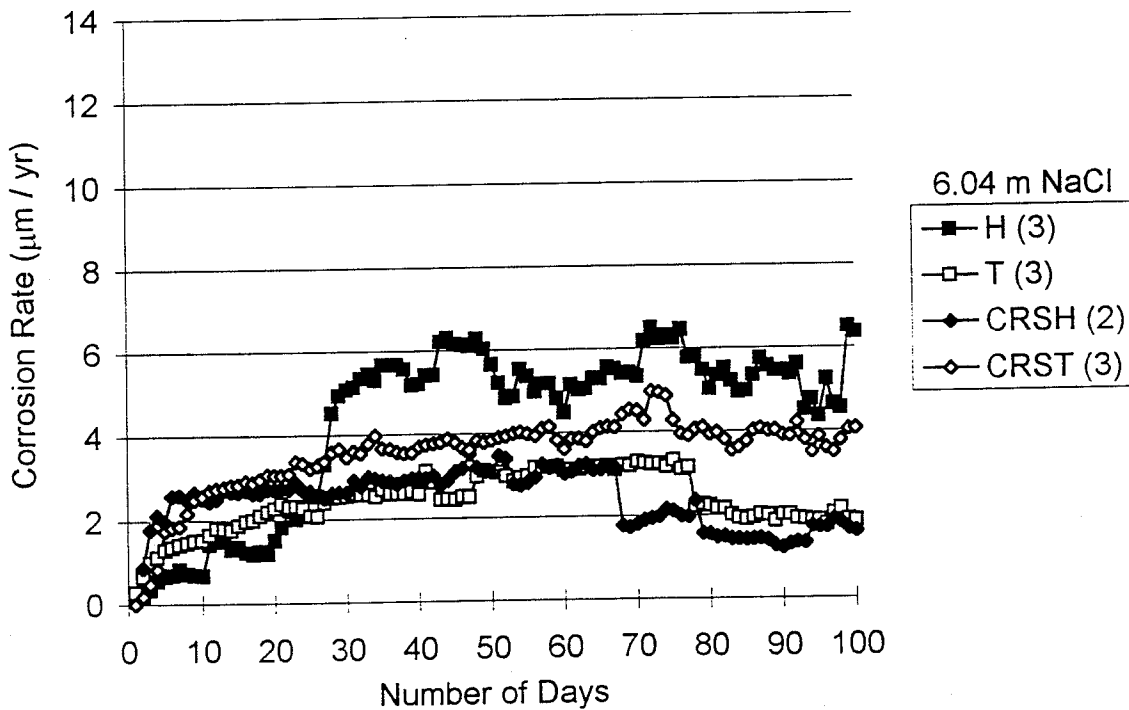


FIGURE 9 Corrosion Rate Versus Time for Macrocell Tests, 6.04 Molal Ion (15 percent) Solution of NaCl (1 μm = 0.025 in.), Comparing H, T, CRSH and CRST Steels (1 μm = 0.025 in.)

Overall, the corrosion-resistant steels exhibited consistently lower corrosion than the conventional steels.

Stage 2 - Bench Scale Time-to-Corrosion Tests

The results of the Southern Exposure and cracked beam tests are illustrated in Figures 10-13 in terms of corrosion rate in $\mu\text{m}/\text{yr}$ versus the number of weeks over which the data was recorded. The number of specimens used in each average curve is indicated on the figures. During the course of the tests, the potential of both the top and bottom mats was measured, as was the mat-to-mat resistance. In some cases, the corrosion potential of the bottom mat became more negative than -0.300 volts. It was assumed that this was due to the presence of sodium chloride. In most cases, the macrocell corrosion rates on these specimens dropped significantly and, therefore, are not used in developing the average curves.

Figure 10a presents the basic comparison for the Southern Exposure tests for the four types of steel. Initially, CRST exhibited the highest corrosion rate, but, after 24 weeks, it consistently exhibited the lowest corrosion rate of the four steels, dropping to less than half the rate exhibited by the other steels as the tests proceeded. An evaluation of the corrosion potential and mat-to-mat resistance of the steels indicated that, as the tests progressed, the corrosion potentials of the bottom and top mats were nearly identical for all specimens, but that the mat-to-mat resistance of the CRST specimens was generally higher than that of the other steels, especially after 28 weeks. The cracked beam specimens (Figure 10b) appear to give a different story, with the CRSH steel exhibiting considerably higher corrosion rates than the other three steels. In this case, the H and T steels exhibited the lowest corrosion rates for most of the test period. However, the corrosion rate of the CRST steel dropped below that of the T steel 42 weeks into the test. The results illustrated in Figures 10a and 10b suggest that the previous standard 48-week time period for the Southern Exposure specimens (9) should logically be extended, perhaps to two years.

The effect of combining conventional and corrosion-resistant steel is exhibited in Figures 11a and 11b for Southern Exposure and cracked beam specimens, respectively. In each figure, corrosion rates for combined H and CRST steels are shown. In each case, the first steel listed represents the top mat and the second steel represents the bottom mat. For both the SE and cracked beam specimens, the H/CRST combination exhibits significantly less corrosion than does the CRST/H combination. This limited comparison appears to indicate that a significant portion of the low corrosion rate provided by the corrosion-resistant steels lies with their behavior at the cathode, not just at the anode, suggesting that some of the corrosion products that form at the cathode (presumably when the steel initially passivates) may limit access of oxygen to the reinforcing bar. Additional study will be necessary to evaluate the details of the corrosion mechanism of the CRST and CRSH steels. However, Figures 11a and 11b suggest that it would not be wise to mix conventional and corrosion-resistant steel in the same structure.

The relative effects of the corrosion inhibitors on the CRST and CRSH steels are illustrated in Figures 12a and 12b for Southern Exposure and cracked beam specimens, respectively. The symbols used in Figures 12a and 12b indicate the type of corrosion inhibitor, using the letter "O" for organic and "I" for inorganic (calcium nitrite), following the basic designation of the steel. The rate of corrosion with both the organic and inorganic corrosion inhibitors is significantly below that exhibited by the same steels without the corrosion inhibitor, with the possible exception of the CRSH steel cast in concrete containing inorganic corrosion inhibitor (CRSHI). The higher corrosion rate exhibited in this case occurs for both the SE and cracked beam specimens. It is important to note that the water-cement ratio of 0.5 used in this study is generally acknowledged to provide good performance for the organic corrosion inhibitor (18, 19). However, it is higher than recommended for use with calcium nitrite (19). A water-cement ratio of 0.5 was selected to increase the rate at which the sodium chloride reached the upper mat of steel. It does not, however, represent the high quality concrete that should be used in transportation structures, and the results illustrated in Figures 12a and 12b should be evaluated with this in mind. The very low corrosion rates exhibited by the CRSHO, CRSTO, and CRSTI test specimens speaks well for both corrosion inhibitors. It would be useful to expand the current study to include comparisons using the corrosion inhibitors with conventional reinforcement.

The corrosion performance of epoxy-coated H, CRSH, and CRST steels is illustrated in Figure 13. The corrosion rates represent the rates on the exposed portion of the reinforcing bar (28 mm^2 per bar), not the total bar surface. The results show that initiation of corrosion was significantly delayed for the two corrosion-resistant steels. Corrosion initiated at about 10 weeks for the EH steel specimens compared to 32 weeks for the ECRST specimens and 42 weeks for ECRSH specimens, suggesting that the new steel will work very well in conjunction with an epoxy coating. The overall corrosion rates (based on the exposed areas) were much higher than observed for the uncoated steel specimens (Figures 10a, 11a, 12a). This may be due, in part, to the size of the anode relative to the cathode in each case.

The chloride content in the concrete (expressed as a weight of chlorides per unit volume of concrete) at the initiation of corrosion for the test specimens provides a basis for additional comparison of the corrosion resistance exhibited by each of the steels. As shown in Table 2, in each case in which a corrosion-resistant steel served as an anode, the chloride concentration at corrosion initiation in the Southern Exposure specimens was higher than for the corresponding specimen with conventional steel as the anode. For the specimens in Figure 10, corrosion was initiated in the H and T specimens at an average chloride content of $0.6 \text{ kg}/\text{m}^3$, compared to 0.7 and $1.1 \text{ kg}/\text{m}^3$ for the CRSH and CRST specimens, respectively.

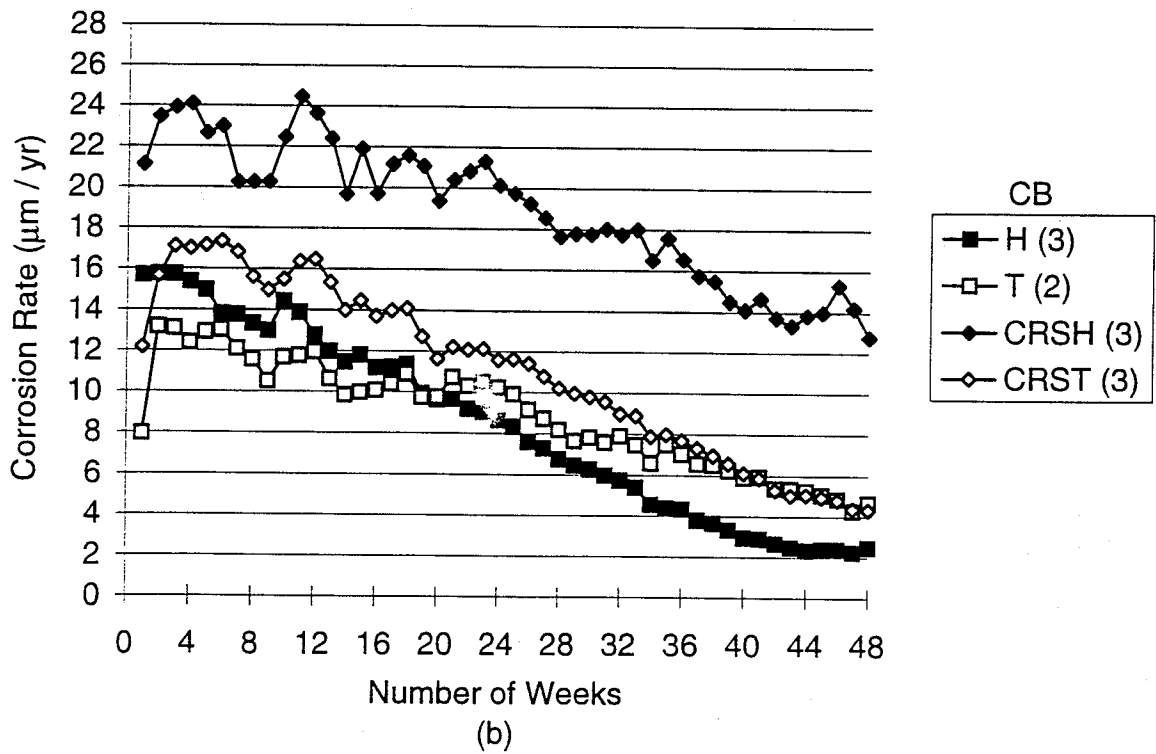
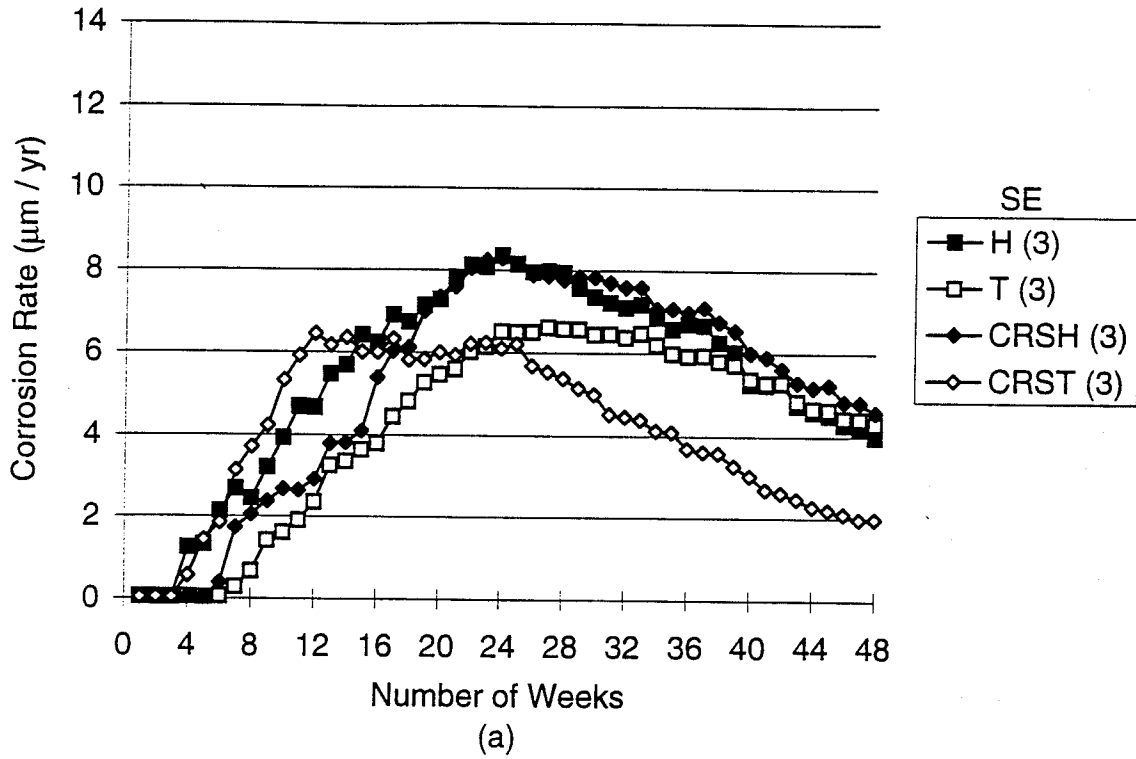


FIGURE 10 Corrosion Rate Versus Time for (a) Southern Exposure and (b) Cracked Beam Tests, Comparing H, T, CRSH and CRST Steels (1 μm = 0.025 in.)

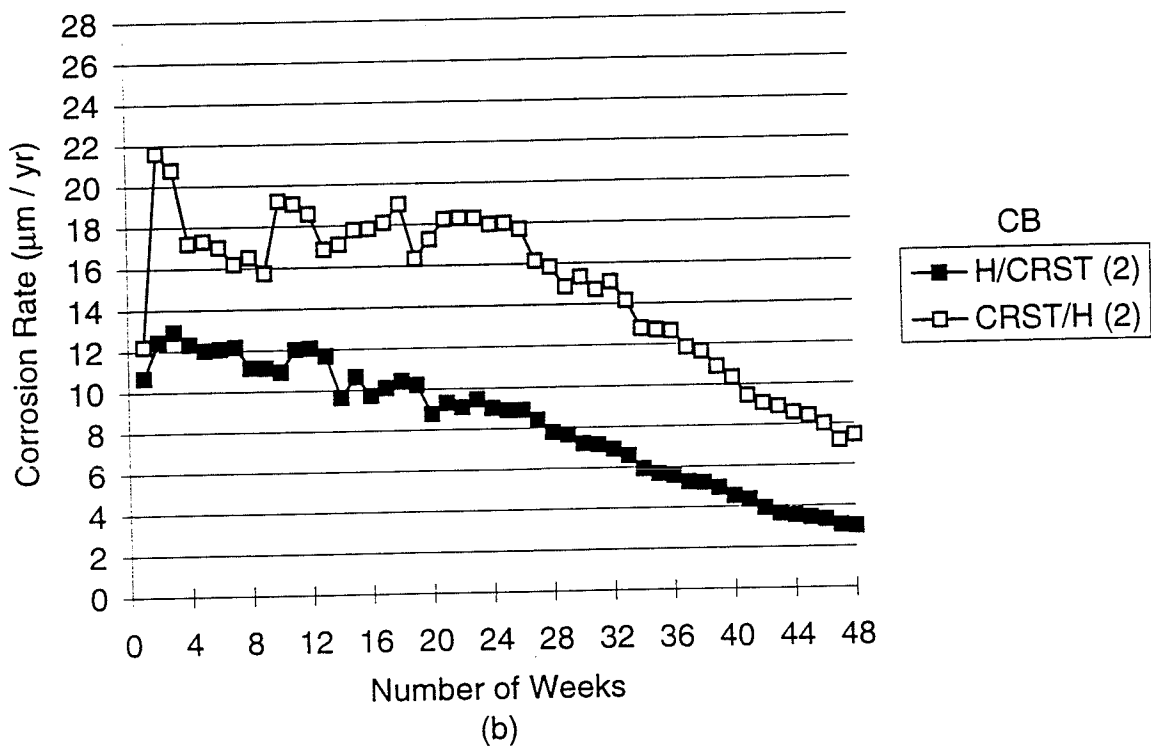
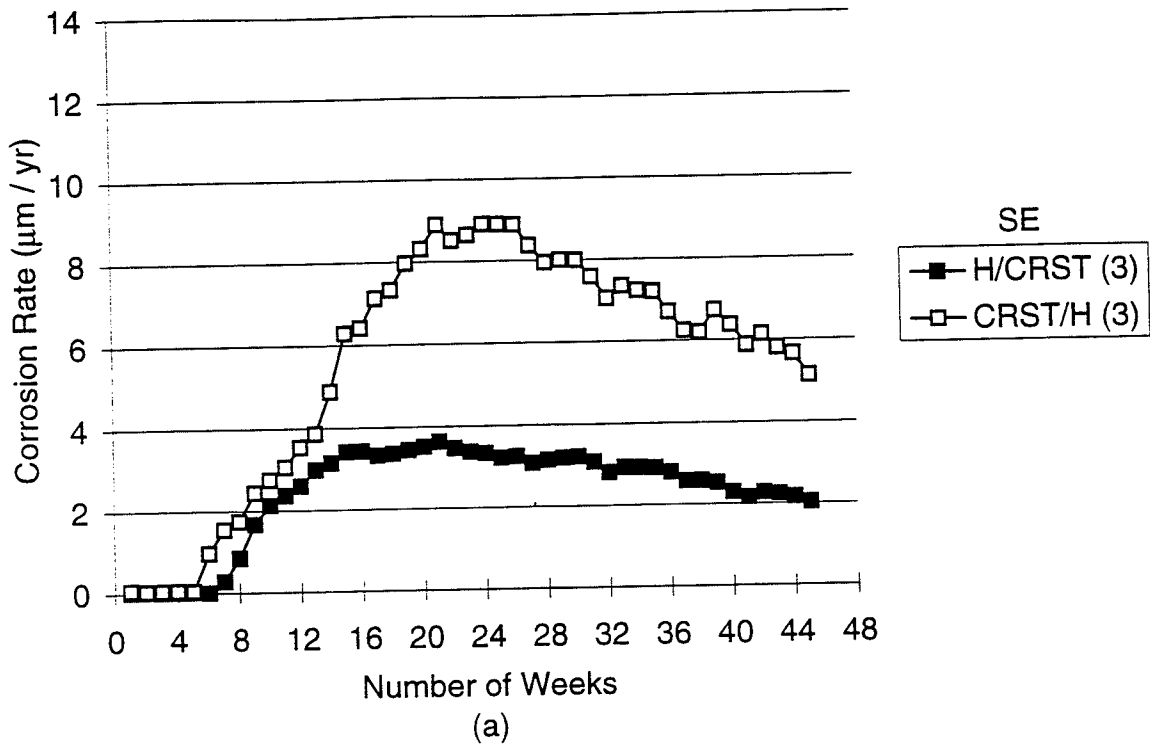


FIGURE 11 Corrosion Rate Versus Time for (a) Southern Exposure and (b) Cracked Beam Tests, Comparing Combinations of Steel: H Steel as Anode and CRST Steel as Cathode (H/CRST); and CRST Steel as Anode and H Steel as Cathode (CRST/H) (1 μm = 0.025 in.)

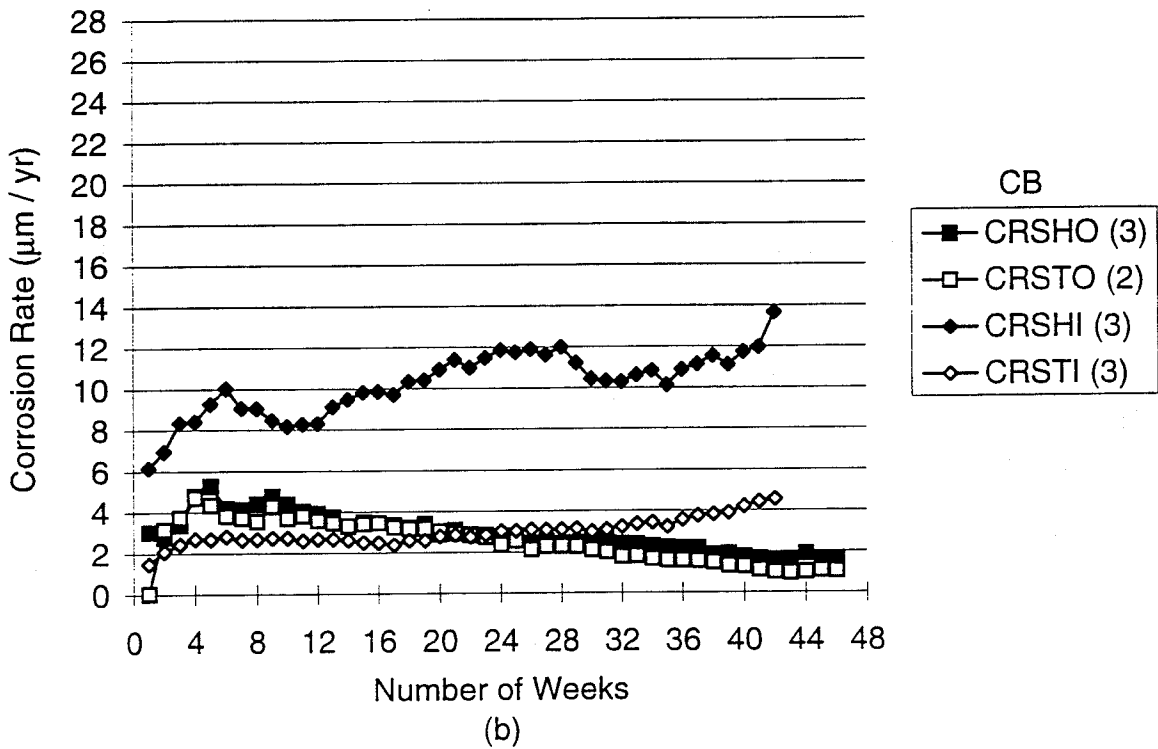
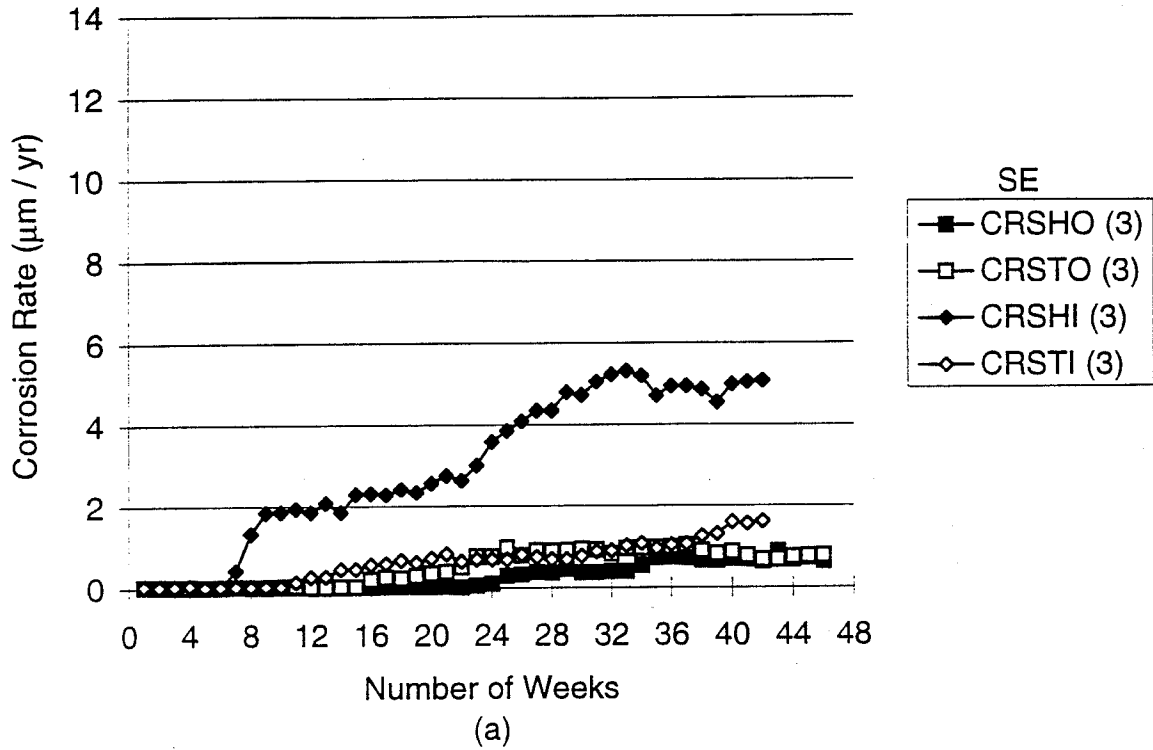


FIGURE 12 Corrosion Rate Versus Time for (a) Southern Exposure and (b) Cracked Beam Tests, Comparing CRSH and CRST Steels in Concrete with Organic (CRSHO, CRSTO) and Inorganic (CRSHI, CRSTI) Corrosion Inhibitors ($1 \mu\text{m} = 0.025 \text{ in.}$)

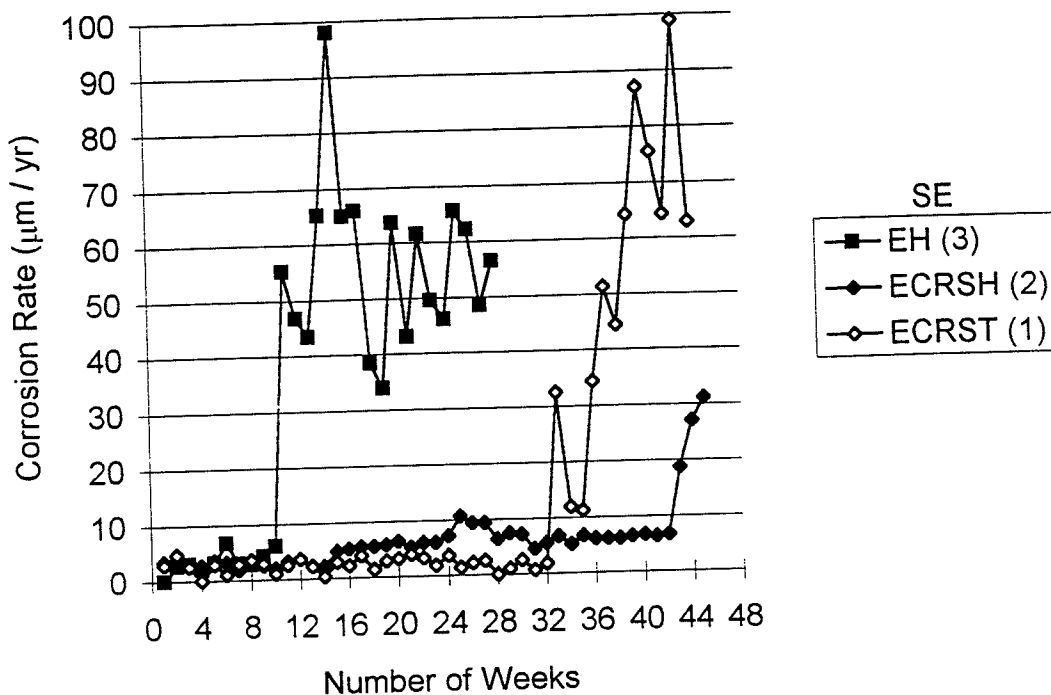


FIGURE 13 Corrosion Rate Versus Time for Southern Exposure Tests of Epoxy-Coated H, CRSH and CRST Steels ($1 \mu\text{m} = 0.025 \text{ in.}$)

TABLE 2 Chloride Ion Concentration in Southern Exposure Specimens at Corrosion Initiation

Specimen	No. in Average	Average (kg/m^3)
H	3	0.6
T	3	0.6
CRSH	3	0.7
CRST	3	1.1
H/CRST	3	0.7
CRST/H	3	1.7
CRSHO	2	3.0
CRSTO	3	0.2
CRSHI	3	1.7
CRSTI	3	3.1
EH	2	0.4
ECRSH	1	2.3
ECRST	2	3.7

For the specimens illustrated in Figure 11, corrosion initiated in the H/CRST specimen at a chloride concentration of 0.7 kg/m^3 compared to 1.7 kg/m^3 in the CRST/H specimen. For epoxy-coated specimens shown in Figure 13, corrosion initiated at a concentration of 0.4 kg/m^3 in the EH specimens compared to 2.3 and 3.7 kg/m^3 in the ECRSH and ECRST specimens, respectively. The chloride ion concentrations at corrosion initiation for the specimens cast in concrete containing corrosion inhibitor ranged from 0.2 , for the CRSTO specimens, to 3.1 , for CRSTI specimens.

The chloride ion concentration does not reflect the overall corrosion performance of any of the steels. It does, however, contribute to the overall picture, with the key observation being that the new steels consistently exhibited a higher concentration at corrosion initiation compared to the conventional steels. The number of specimens listed in Table 2 does not match those listed in Figures 10-13 in all cases. The reason for this discrepancy is that, in some cases, salt reached the cathode after corrosion had initiated and, therefore, some specimens that are included in Table 2 have been removed from the corrosion rate calculations used for the figures. In the case of one ECRSH specimen and one CRSHO specimen, corrosion never initiated; these specimens, however, are used in the figures. Finally, one EH specimen was not sampled due to an error in reading the voltage drop across the 10 ohm resistor.

Stage 3 – Evaluation of Effect of Deicer Type and Concentration

The goal of Stage 3 was to evaluate the relative corrosion performance of the four steels when subjected to corrosion initiators other than sodium chloride. Calcium chloride and calcium magnesium acetate are used. The comparisons are made on a molal ion basis, since it is the ion concentration that controls the ice melting capability of a compound. At any molal ion concentration, calcium chloride will provide a higher chloride ion content than NaCl.

The results of this analysis are illustrated in Figures 14 and 15 for the 0.4 , and 1.6 molal ion concentrations, respectively. At the 6.04 m ion concentration, the addition of calcium chloride to the simulated pore solution resulted in the formation of a large amount of precipitate (calcium hydroxide), and the addition of calcium magnesium acetate resulted in the formation of a gel-like substance. The test results at these high concentrations were highly unstable and are, therefore, not included in this analysis.

Figures 14a and 14b illustrate the corrosion performance of the four steels at a 0.4 m ion concentration for CaCl_2 and CMA. For calcium chloride, the CRST specimens exhibited a slightly lower corrosion rate than the H specimens (both at about $2 \text{ } \mu\text{m/yr}$), followed by the CRSH specimens (about $3 \text{ } \mu\text{m/yr}$) and finally the T specimens ($4 \text{ } \mu\text{m/yr}$). For the 0.4 m ion CMA macrocells, at the end of 100 days, the CRSH and CRST specimens exhibited the lowest corrosion rates (2.5 and $3.5 \text{ } \mu\text{m/yr}$, respectively), followed by the T and the H specimens (4 and $5 \text{ } \mu\text{m/yr}$, respectively). The corrosion rates are generally similar to those exhibited by the four steels in the 0.4 m ion NaCl macrocells (Figure 6).

The results for the 1.6 molal ion concentrations of CaCl_2 and CMA are shown in Figures 15a and 15b, respectively. For CaCl_2 , CRST provided the lowest corrosion rate ($4 \text{ } \mu\text{m/yr}$), while CRSH provided the highest corrosion rate ($7 \text{ } \mu\text{m/yr}$), with the T and H steels in between (4.5 and $5 \text{ } \mu\text{m/yr}$). For the 1.6 m ion concentration of CMA, the CRSH, CRST, and H steels exhibited very low corrosion rates (less than $1 \text{ } \mu\text{m/yr}$ at 100 days); even the T steel exhibited a corrosion rate no higher than $3 \text{ } \mu\text{m/yr}$. Calcium magnesium acetate is "sold" as a deicing chemical that results in lower corrosion rates than chlorides, which appears to be supported by the results illustrated in Figure 15b.

Stage 4 – Mechanical Properties

The results of the mechanical tests are listed in Table 3. They indicate that the Thermex treated steels meet all strength and ductility requirements for Grade 60 ASTM A 615 (4) steel. The nonheat-treated steels produced by Florida Steel also meet the requirements of ASTM A 615, but for a lower yield strength. The lower yield strength results because of the relatively low carbon content used for these steels. The satisfactory strength and ductility performance of the CRST steel suggests that there should be no problems in using it as a structural replacement for standard ASTM A 615 reinforcement.

Summary of Findings

Overall, the experimental steels evaluated in this study exhibited increased corrosion resistance in comparison to the conventional steels evaluated. When subjected to sodium chloride, both the macrocell and Southern Exposure specimens showed that CRST steel exhibits consistently lower corrosion rates than do the two conventional steels. CRSH steel exhibited low corrosion rates in the macrocell tests, but not in the Southern Exposure test. The epoxy-coated CRSH and CRST steels exhibited significantly less corrosion than the epoxy-coated H steel when the epoxy coating was penetrated. Although the phosphorous content of the new steels exceeded that allowed in normal practice (4, 5), both the CRSH and the CRST steels exhibited adequate ductility. The CRST steel met the full strength requirements for a Grade 60 steel; the

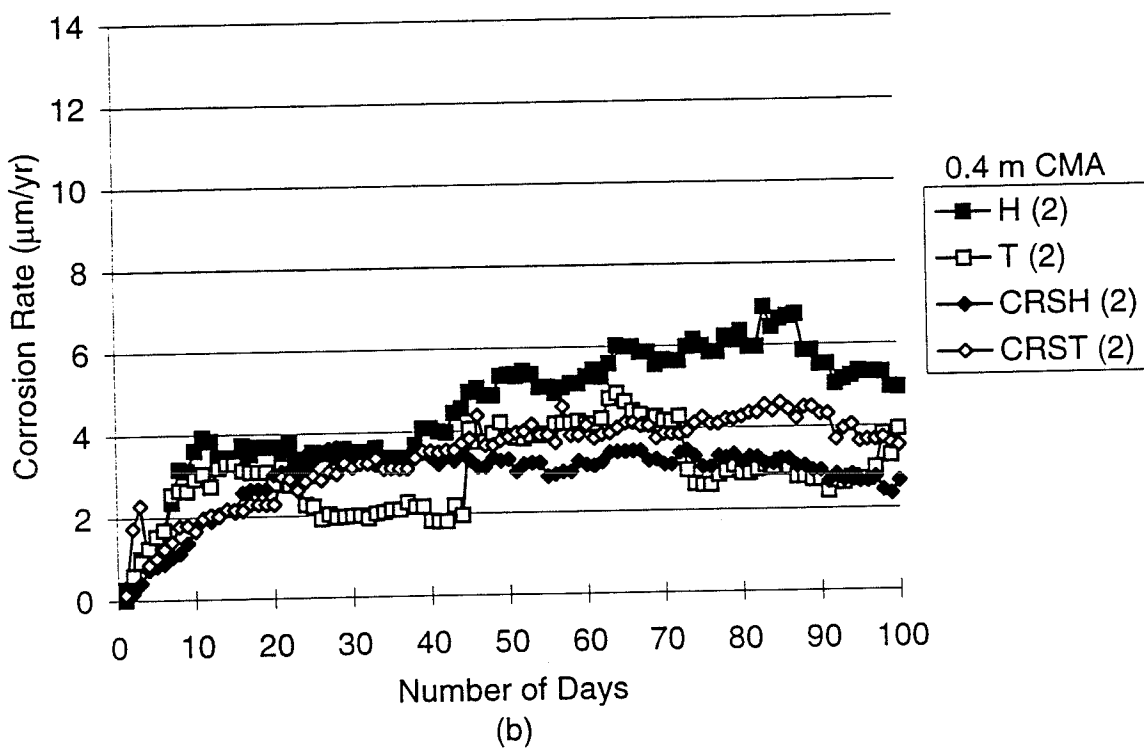
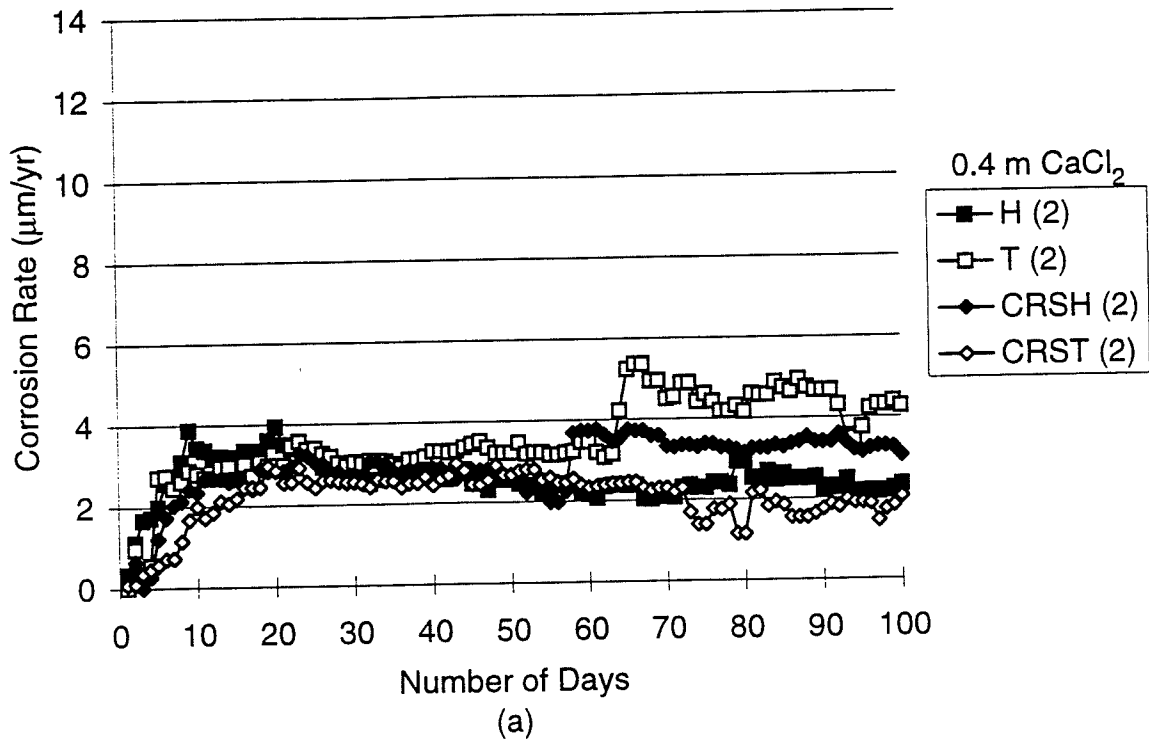


FIGURE 14 Corrosion Rate Versus Time for Macrocell Tests for (a) 0.4 Molal Ion Solution of Calcium Chloride and (b) 0.4 Molal Ion Solution of Calcium Magnesium Acetate, Comparing H, T, CRSH and CRST Steels (1 µm = 0.025 in.)

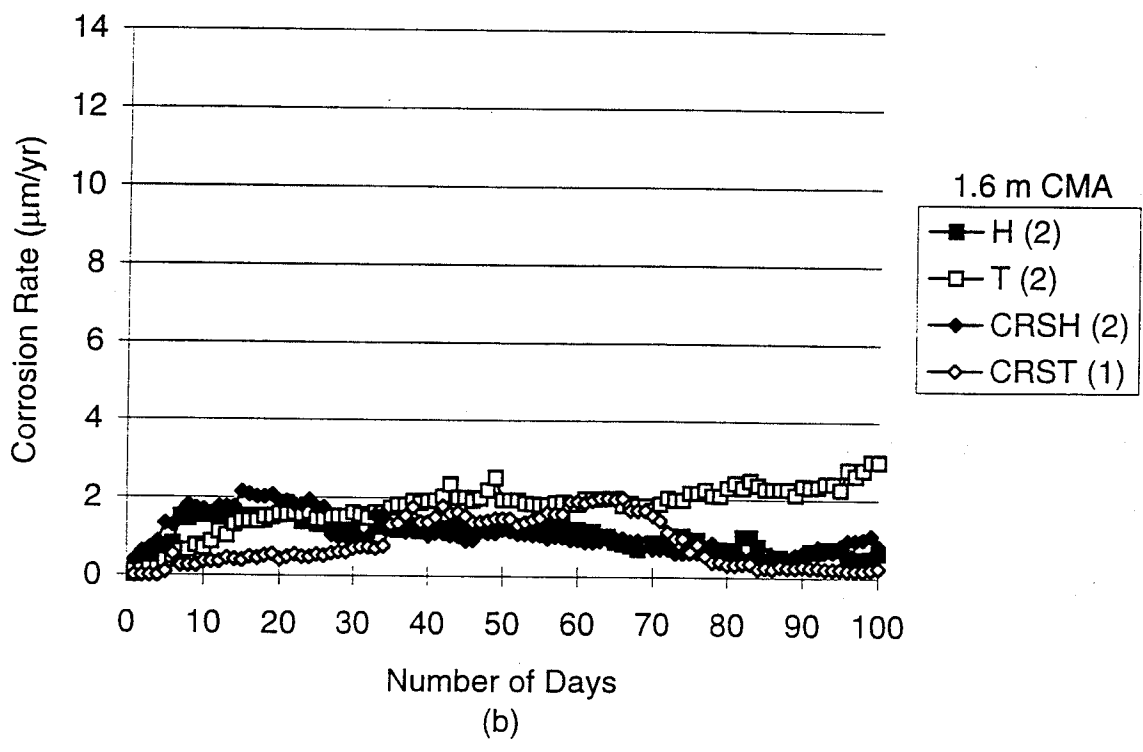
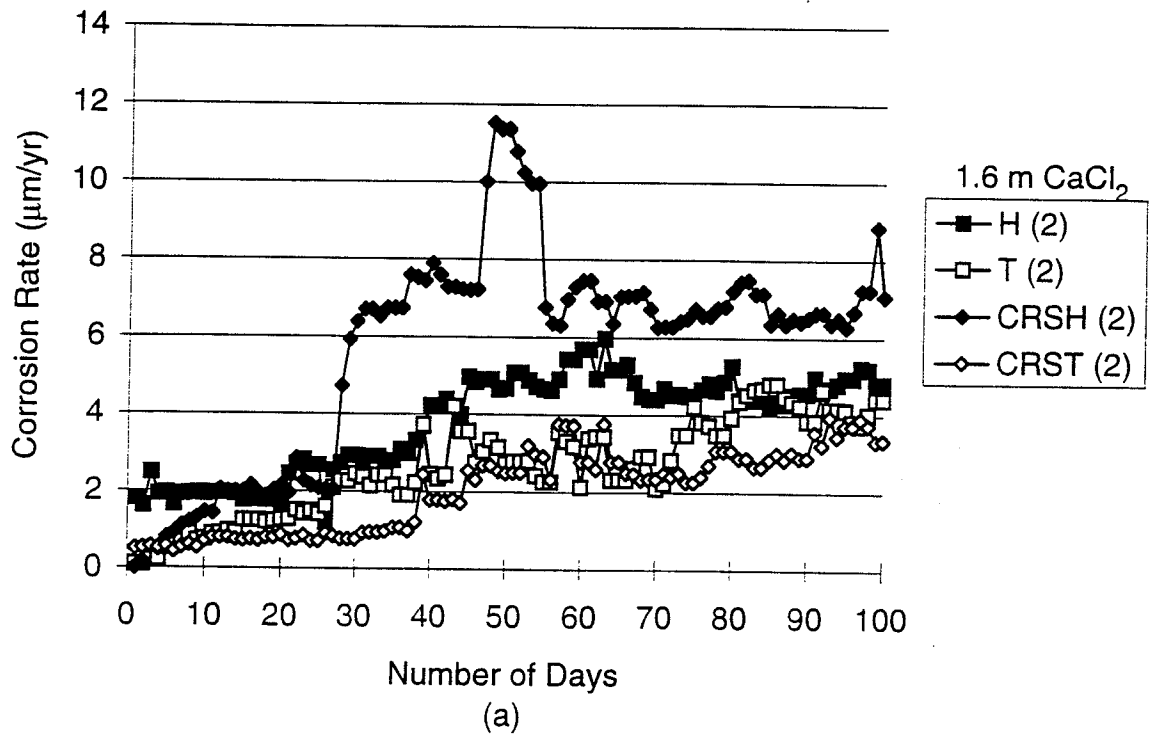


FIGURE 15 Corrosion Rate Versus Time for Macrocell Tests for (a) 1.6 Molal Ion Solution of Calcium Chloride and (b) 1.6 Molal Ion Solution of Calcium Magnesium Acetate, Comparing H, T, CRSH and CRST Steels (1 μm = 0.025 in.)

CRSH steel, without benefit of heat treatment, would require the use of additional alloying elements to increase the yield strength. It would have been fully satisfactory as a Grade 40 reinforcement.

TABLE 3 Mechanical Test Results for 16 mm (No. 5) Steel Reinforcing Bars

Steel Type	Heat ID No.	Yield Strength MPa	Tensile Strength MPa	Elongation percent	Bend Test
H	K5-5546	384	612	17.3	pass
T	K5-5546	545	702	12.3	pass
H	K4-3064	--	--	--	pass
T	K4-3064	585	701	15.0	pass
H	2-0977	442	681	13.9	pass
CRSH	K3-1725	350	565	22.7	pass
CRST	K3-1725	570	700	12.0	pass

-- not tested

Based on the performance exhibited in these tests, the continued evaluation of the new steel seems justified and such continued evaluation, therefore, is recommended.

PLANS FOR IMPLEMENTATION

Based on the evaluation described in this report, it is recommended that efforts be pursued to implement the new corrosion-resistant steel into practice. It is recommended that, initially, the original guidelines provided for microalloying (1-3) be followed (listed in Table 1), since only one experimental steel has been evaluated. It is further recommended that a quenching and tempering process, such as Thermex heat treatment, be used to allow a Grade 60 steel to be obtained economically. The new steel should be required to pass all strength and ductility requirements of ASTM A 615 (4).

Implementation of the new steel will require a number of steps. On the experimental front, additional bench-scale tests should be carried out to provide longer-term supporting evidence of the benefits of the new reinforcement. It appears that at least some of the corrosion-resistant qualities of the new steel come from the type of corrosion products formed. The question, which can only be answered in the long term, is whether or not these corrosion products will cause delamination of concrete. Up to one year, the corrosion products appear to decrease the corrosion rate without causing structural damage to the concrete. Only longer-term tests will demonstrate any tendency of the corrosion products to cause delamination.

As part of the implementation program, additional heats of the new reinforcement covering the recommended range of alloying elements should be produced and evaluated. As the test data is obtained, the results should be presented to state highway departments, the Transportation Research Board, and the Federal Highway Administration to aid in the development of demonstration projects in which the new steel can be used. A special opportunity for implementation of the new steel lies in its use with an epoxy coating. As illustrated in Figure 13, the new reinforcement appears to provide significantly delayed corrosion initiation compared to conventional steel when it is epoxy coated.

Overall, the implementation steps must include efforts in ASTM Subcommittee A01.05 on Steel Reinforcement to develop a specification for the new reinforcing steel, identical to ASTM A 615 (4) with the exception that it contain altered requirements for chemistry.

CONCLUSIONS

The following conclusions are based on the experimental results and analyses presented in this report.

1. The microalloying procedure, using increased phosphorous, chromium, and copper, improves the corrosion resistance of steel reinforcing bars cast in concrete and subjected to deicing chemicals. The resulting corrosion rate is approximately one-half of the corrosion rate exhibited by conventional reinforcing steel.
2. The use of a quenching and tempering heat treatment process that follows hot rolling of reinforcing steel appears to provide additional corrosion resistance, when used in conjunction with the microalloying procedure. In this study, heat-treated bars exhibited improved corrosion resistance more consistently than nonheat-treated bars. The quenching and tempering process produces a reinforcing steel with higher yield and tensile strengths.
3. A phosphorous content in excess of 0.06 percent did not cause the corrosion-resistant steel evaluated in this study to become brittle.
4. Although corrosion products were not studied, the electrochemical measurements made in this study provide evidence that the corrosion resisting mechanisms exhibited by the new reinforcing steel involve the deposition of protective corrosion products at both the anode and the cathode.
5. It is recommended that the new reinforcing steel not be combined with conventional reinforcing steel in reinforced concrete structures.
6. Additional study appears to be justified to 1) add to the database supporting the corrosion resistant properties of the new reinforcing steel and 2) gain greater insight into the nature of the corrosion resistant process. This additional evaluation of the steel should be carried out in conjunction with corrosion inhibiting admixtures.
7. The new steel performed well when used in conjunction with an epoxy coating.
8. The new reinforcement offers the potential of economically providing a measurable improvement in the corrosion performance of reinforced concrete transportation structures subjected to chlorides and deicing chemicals.
9. Implementation of the new reinforcing steel will require 1) additional corrosion tests to fully document the corrosion-resistant properties of the reinforcement, 2) the development of standard specifications for the material, and 3) the execution of demonstration projects in which the new reinforcing steel is applied in practice. Special attention should be given to using the new steel in conjunction with epoxy coating.

INVESTIGATOR PROFILE

The study was directed by David Darwin, Deane E. Ackers Professor of Civil Engineering and Director of the Structural Engineering and Materials Laboratory, and Carl E. Locke, Jr., Professor of Chemical and Petroleum Engineering and Dean of Engineering at the University of Kansas. Darwin has been active in many aspects of reinforced concrete and concrete materials research, including work as the principal investigator on the development of two tests to rapidly determine the corrosion effects of deicing chemicals on reinforcing steel in concrete. Those tests, the rapid corrosion potential and macrocell tests, were updated and used in this study to compare corrosion performance. Darwin is currently directing a Civil Engineering Research Foundation/National Science Foundation/Industry study to improve the development characteristics of reinforcing bars.

Locke is a nationally recognized expert in the field of corrosion of reinforcing steel. His research has addressed the electrochemistry of the corrosion of steel in concrete, the effect of cathodic protection currents on the bond strength of reinforcing steel to concrete, the effects of calcium magnesium acetate on corrosion of steel in concrete, and (with Darwin) the development of the rapid tests for the effects of deicing chemicals on corrosion of reinforcing steel in concrete. He holds four patents in the field of corrosion protection.

The University of Kansas Structural Engineering and Materials Laboratory and Chemical and Petroleum Engineering laboratories are fully equipped to carry out structural engineering, engineering materials, and corrosion studies for application in large-scale structures.

REFERENCES

1. Development of New Corrosion-Resistant Steel (CRS) at Tata Steel, *Report*, Tata Iron and Steel Co., Ltd., Jamshedpur, India, 1991.
2. R. Jha, S. K. Singh, and A. Chatterjee. Development of New Corrosion-Resistant Steel Reinforcing Bars. *Materials Performance*, NACE, Vol. 31, No. 4, Apr 1992, pp. 68-72.
3. Proposed Specification for Corrosion-Resistant Deformed Steel Bars for Concrete Reinforcement. Tata Iron and Steel Co., Ltd., Jamshedpur, India, 1991.

4. ASTM. Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement. (ASTM A 615/A 615M-94), *1995 Annual Book of ASTM Standards*, Vol. 1.04, American Society of Testing and Materials, Philadelphia, PA, pp. 300-304.
5. ASTM. Standard Specification for Low-Alloy Steel Deformed Bars for Concrete Reinforcement. (ASTM A 706/A 706M-93a), *1995 Annual Book of ASTM Standards*, Vol. 1.04, American Society of Testing and Materials, Philadelphia, PA, pp. 342-346.
6. T. Yonezawa, V. Ashworth, and R. P. M. Procter. Study of the Pore solution Composition and Chloride Effects on the Corrosion of Steel in Concrete. *Corrosion*. Vol. 44, No. 7, July 1988.
7. William F. Perenchio. Wiss, Janney, Elstner Associates, Inc., personal communication, Dec. 1992.
8. Donald W. Pfeifer and Mauro J. Scali. Concrete Sealers for Protection of Bridge Structure., *NCHRP Report No. 244*. National Cooperative Highway Research Program, Transportation Research Board, Washington, D. C., Dec. 1981.
9. Donald W. Pfeifer, J. Robert Sandgren, and Alexander Zoob. Protective Systems for New Prestressed and Substructure Concrete. *Report No. FHWA/RD-86/193*, Federal Highway Administration, McLean, VA, Apr. 1987.
10. Sonia L. Martinez, David Darwin, Steven L. McCabe, and Carl E. Locke. Rapid Test for Corrosion Effects of Deicing Chemicals in Reinforced Concrete. *SL Report 90-4*. University of Kansas Center for Research, Inc., Lawrence, KS, Aug. 1990.
11. ASTM. Standard Specification for Epoxy-Coated Reinforcing Steel Bars. (ASTM A 775/A 775M-94d, *1995 Annual Book of ASTM Standards*, Vol. 1.04, American Society of Testing and Materials, Philadelphia, PA, pp. 406-411.
12. ASTM. Standard Specification for Standard Sand. (ASTM C 778-92a), *1994 Annual Book of ASTM Standards*, Vol. 4.01, American Society of Testing and Materials, Philadelphia, PA, pp. 323-325.
13. Cecil C. Chappelow, A. Dean McElroy, Robert R. Blackburn, David Darwin, Frank G. deNoyelles, and Carl E. Locke. *Handbook of Test Methods for Evaluating Chemical Deicers*, Strategic Highway Research Program, National Research Council, Washington, D.C., 1992.
14. H. Farzammehr. Pore Solution Analysis of Sodium Chloride and Calcium Chloride Containing Cement Pastes. *Master of Science Thesis*. University of Oklahoma, Norman, OK, 1985.
15. H. Farzammehr, Changiz Dehghanian, and Carl E. Locke. Study of the Effects of Cations on Chloride Caused Corrosion of Steel in Concrete. *Revista Técnica de la Facultad de Ingeniería*, Univ. Zulia, Venezuela, Vol. 10, No. 1, 1987, pp. 33-40.
16. P. D. Cady and E. J. Gannon. Standard Test Method for Chloride Content in Concrete Using the Specific Ion Probe. *Condition Evaluation of Concrete Bridges Relative to Reinforcement in Concrete*, Vol. 8, Procedure Manual, SHRP-S/FR-92-110; Strategic Highway Research Program, National Research Council, Washington, D.C., 1992. pp. 85-105.
17. Denny A. Jones. *Principles and Prevention of Corrosion*. MacMillan Publishing Company, New York, 1992.
18. C. K. Nmai and E. K. Attiogbe. Effect of Chemical and Mineral Admixtures on the Corrosion of Steel in Concrete. *Corrosion/92*, Paper No. 201 (Houston, TX: NACE, 1992).
19. N. S. Berke, M. P. Dallaire, M. C. Hicks, and R. J. Hoopes. Corrosion of Steel in Cracked Concrete. *Corrosion*, Vol. 49, No. 11, Nov. 1993, pp. 934-943.

NOTATION

CB	cracked beam test
CMA	calcium magnesium acetate
CRS	corrosion-resistant steel
CRSH	hot-rolled corrosion-resistant steel
CRSHI	CRSH steel cast in concrete containing an inorganic corrosion inhibiting admixture
CRSHO	CRSH steel cast in concrete containing an organic corrosion inhibiting admixture
CRST	quenched and tempered (Thermex-treated) corrosion-resistant steel

CRSTI	CRST steel cast in concrete containing an inorganic corrosion inhibiting admixture
CRSTO	CRST steel cast in concrete containing an organic corrosion inhibiting admixture
CRST/H	CB or SE specimen with CRST steel in top mat and H steel in bottom mat
ECRSH	SE specimen with epoxy-coated CRSH steel in top mat and uncoated CRSH steel in bottom mat
ECRST	SE specimen with epoxy-coated CRST steel in top mat and uncoated CRST steel in bottom mat
EH	SE specimen with epoxy-coated EH steel in top mat and uncoated EH steel in bottom mat
H	hot-rolled conventional steel
H/CRST	CB or SE specimen with H steel in top mat and CRST steel in bottom mat
SE	Southern Exposure test
T	quenched and tempered (Thermex-treated) conventional steel