

**IDEA Program (Stage 1) Report
for the Period June 1994 through September 1994
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PROJECT 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 would be greatly enhanced if the corrosion resistance of reinforcing steel were improved. This study involves the evaluation of a concrete reinforcing steel with 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 new steel in concrete structures. During Stage 1 of the project, this has been accomplished through the use of short-term tests to rapidly determine the corrosion potential and time-to-corrosion of the steel using small specimens, and through the design and initiation of long-term time-to-corrosion tests on larger specimens. The study involves the evaluation of four types of steel, representing combinations of alloying elements and heat treatment. One form of conventional steel is hot rolled (H) and the other is subjected to a heat treatment immediately following the hot-rolling operation (T). The corrosion resistant steels are obtained through the addition of alloying elements. One form of the steel is hot rolled (CRSH), and the other is subjected to a quenching and tempering heat treatment process (CRST).

The key observations obtained during Stage 1 are provided by the short-term macrocell tests that indicate significant variation in the performance of the H, T, and CRSH steels, but consistently superior performance by the CRST steel when the steels are subjected to sodium chloride at molal ion concentrations ranging from 0.4 to 6.4. The longer term time-to-corrosion tests are under way, but as expected, no significant differences in the performance of the steels have been exhibited during the first 16 weeks of the test program. While the short-term tests are not, in themselves, adequate to justify the immediate application of the new corrosion resistant heat-treated steel in full-scale structures, they provide justification for continuing the study, with emphasis on the results of the long-term tests, and proceeding with the other tests planned for Stage 2.

PROGRESS DESCRIPTION

IDEA PRODUCT

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. This study involves the evaluation of a concrete reinforcing steel with superior corrosion resistant properties. The development of such a steel is based on work by a steel company in India (1, 2) that provides evidence that specific microalloying and rolling procedures can enhance the corrosion resistance of steel reinforcing bars. Using copper, chromium, and phosphorous as alloying elements and heat treating the steel following the rolling process appears to provide increased corrosion resistance. The key goal of the study is to evaluate that corrosion resistance under realistic conditions.

The corrosion of reinforcing steel represents the single largest problem in the durability of highway bridges in the United States. Specific concern involves regions in which reinforced concrete is subjected to chlorides. If the added corrosion resistance of the new steel is demonstrated, its use will greatly enhance the durability and life expectancy of transportation structures, with special emphasis on highway bridges in areas in which deicing chemicals are used and in coastal areas in which the structures are subjected to high salt concentrations, environments in which corrosion protection is essential.

To date, the corrosion performance of the new reinforcing steel has been evaluated using rapid corrosion potential and time-to-corrosion tests in the presence of sodium chloride. Longer term time-to-corrosion tests on bench-scale specimens have been designed and initiated.

INNOVATION

The new reinforcing steel under evaluation 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, and 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 a single reinforcing bar, 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 involves, not the ability of the steel to be more corrosion resistant in the atmosphere, which seems to have been amply established in earlier studies, but to demonstrate 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. 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 chlorides so that macrocorrosion cells can develop.

Two general categories of test specimen have been developed to resolve that 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 currently accepted in U.S. practice. As originally proposed, the first four months of the study have involved the fabrication and initiation of both short-term and long-term tests. The short-term tests currently indicate that the new reinforcing steel, with both the new alloying elements and heat treatment, consistently provides improved corrosion protection. However, practical application of the steel must await the results of the long-term tests, which will become available during Stage 2 of the project.

PROGRESS

Work during Stage 1 of the project has involved 1) the performance of short-term tests for rapid corrosion potential and time-to-corrosion using small specimens and 2) the design and initiation of long-term time-to-corrosion tests on larger specimens. The tests involve the side-by-side evaluation of conventional reinforcing steel and the new steel in both hot-rolled and heat-treated (Thermex) form. In addition, the corrosion-resistant Thermex and hot-rolled bars are also tested in specimens containing an inorganic (calcium nitrite) or organic corrosion inhibitor.

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 (6, 7). The tests allow very rapid evaluation of both the corrosion potential and the formation of a corrosion macrocell for reinforcement. The basic test specimen (Figure 1) consists of a length of reinforcing bar embedded in a cylinder of mortar with a water-cement ratio of 0.5. 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.

The corrosion potential test (Figure 2) requires two plastic containers. The test specimen is placed in a 5 liter container along with crushed mortar fill and a simulated pore solution containing a preselected concentration of sodium chloride. 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 is called the corrosion potential of the steel.

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

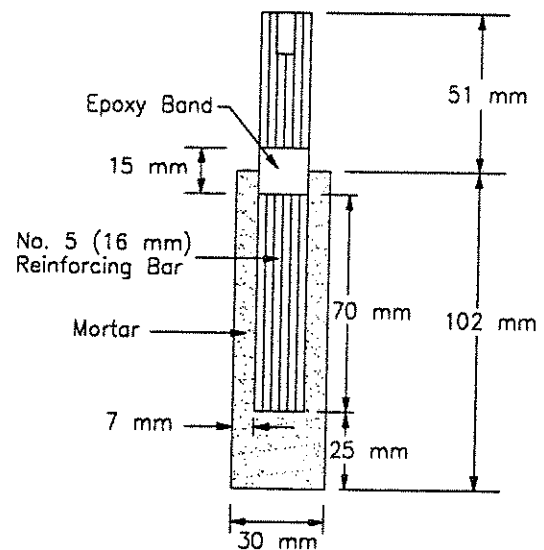


FIGURE 1 Cross section of test specimen used for rapid corrosion potential and time-to-corrosion tests

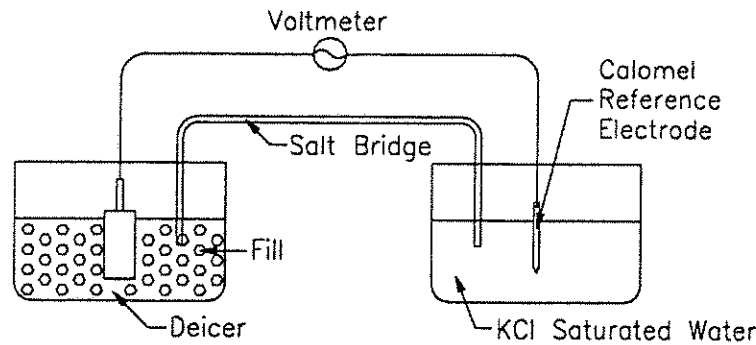


FIGURE 2 Schematic of corrosion potential test configuration

pore solution (a mixture of sodium hydroxide and potassium hydroxide) represents the liquid in the saturated pores and capillaries in concrete (8, 9). 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 voltage difference, "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 by adding an additional test specimen to the container with the pore solution containing sodium chloride. Four additional standard specimens surrounded by mortar fill and immersed in simulated pore solution (with no chlorides added) are placed in a second container. The test specimens in the pore solution containing sodium chloride (anode) are electrically connected through a single 10 ohm resistor to the four 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 CO_2) is bubbled into the liquid surrounding the cathode to insure an adequate supply of oxygen. The rate of corrosion can be measured by measuring the voltage drop across the resistor. In addition to the basic tests, the corrosion-resistant Thermex and hot-rolled bars are also tested in mortar containing calcium nitrite or an organic corrosion inhibitor.

Bench Scale Time-to-Corrosion Tests

Two widely accepted long-term tests will be used to determine the rate of corrosion of reinforcing steel in both uncracked and cracked concrete. The specimens for these tests, all of which are now under way, were fabricated using a water-cement ratio of 0.5 and 19 mm ($3/4$ in.) maximum size aggregate.

The first test specimen, the Southern Exposure or SE specimen (10), consists of a small slab containing two mats of reinforcing steel (Figure 3). The top mat consists of two bars; the bottom mat consists of four bars. The mats are

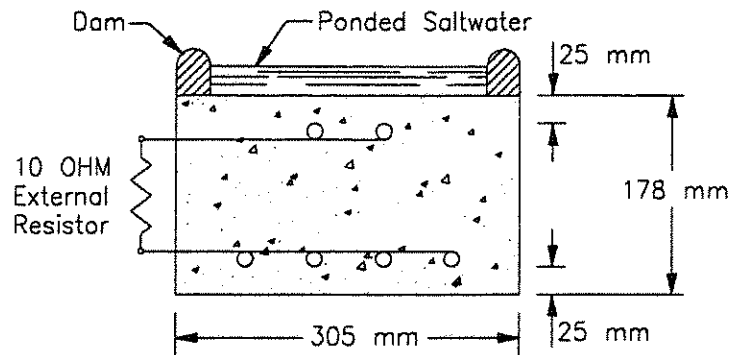


FIGURE 3 Schematic of Southern Exposure (SE) test specimen (after 10) (25.4 mm = 1 in.)

electrically connected across a 10 ohm resistor. The sides of the concrete are sealed with epoxy, and a dam is placed around the edge of the top surface. 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 21°C (70°F) for four days and drying at 38°C (100°F) for three days. The test provides a very severe corrosion environment, and it is generally believed that it can simulate 15-20 years of exposure for marine structures and 30-40 years of exposure for bridges within a 48 week period (11).

The second test specimen, the cracked-beam specimen is half the width of the SE specimen and has one bar on top and two bars on the bottom. After curing of the concrete, the beam is cracked to provide a preselected crack width on the upper surface. A dam is placed on 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. Also, like the SE tests, the cracked-beam tests are carried out for 48 weeks.

Results

The key results from Stage 1 are presented in Figures 4, 5, 6 and 7, showing the relationships between corrosion rate and time for the macrocell tests for specimens immersed in 0.4, 1.0, 1.6, and 6.4 molal ion solutions of sodium chloride, respectively. The corrosion rates are expressed as micrometers per year (25.4 μm = 0.001 in.). These test results illustrate significant variation in the performance of the regular hot-rolled (H), regular Thermex (T), and corrosion-resistant hot-rolled (CRSH) steel, but consistently superior performance by the corrosion-resistant Thermex (CRST) steel.

For the 0.4 molal ion solution of sodium chloride (Figure 4), both the H and T bars exhibit a relatively high rate of corrosion compared to that of the two corrosion-resistant steels. The corrosion rate of CRST is initially lower than that of CRSH, but at 60 days, the two steels exhibit similar corrosion rates. At a molal ion concentration of 1.0 (Figure 5),

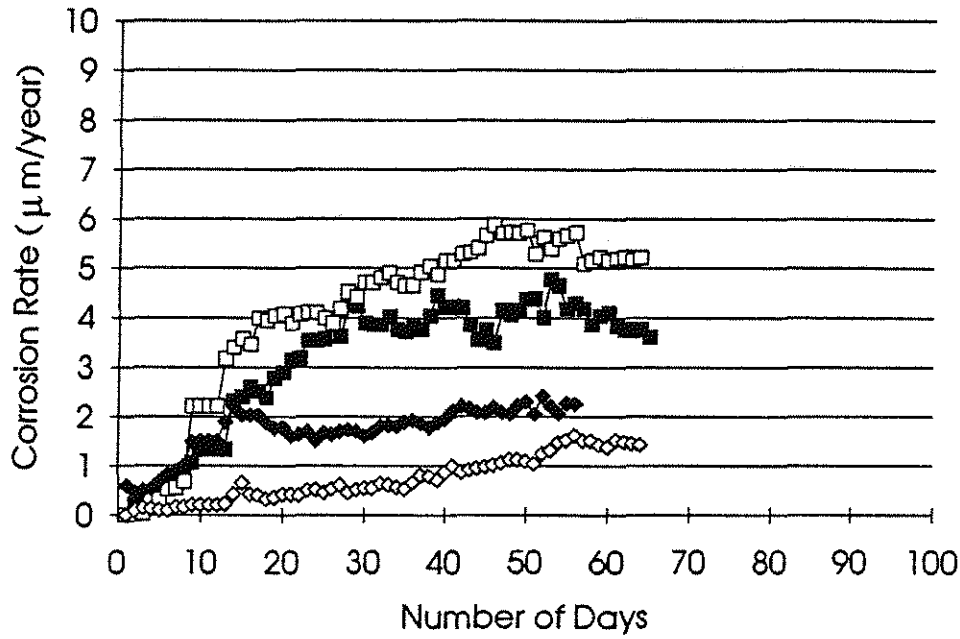


FIGURE 4 Corrosion rate versus time for macrocell test specimens subjected to a 0.4 m ion solution of NaCl (25.4 μm per year = 1 mil per year = 0.001 in. per year)

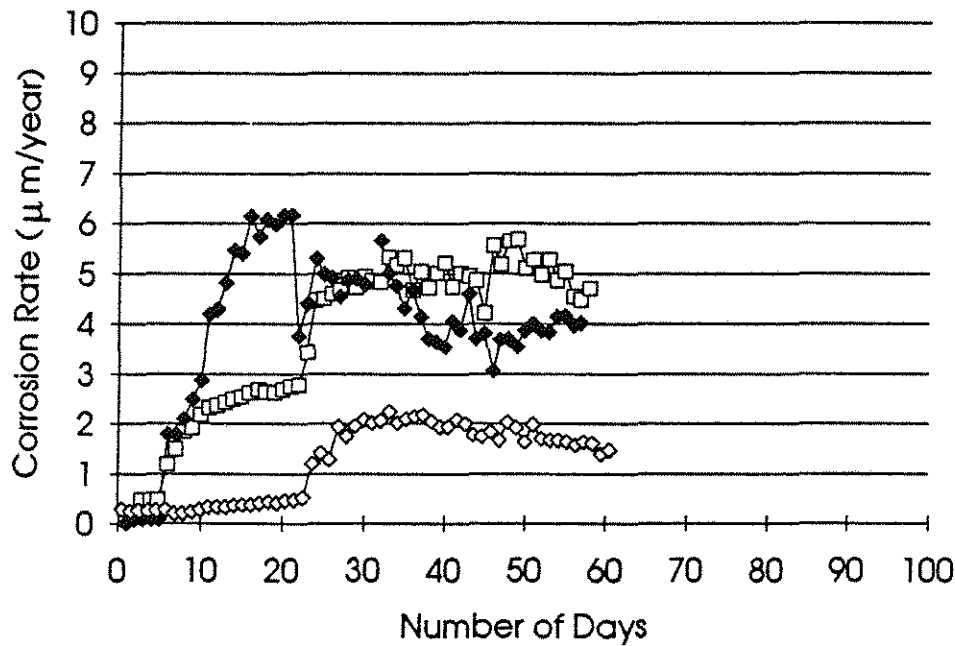


FIGURE 5 Corrosion rate versus time for macrocell test specimens subjected to a 1.0 m ion solution of NaCl (25.4 μm per year = 1 mil per year = 0.001 in. per year)

the T and CRSH steels exhibit the highest rate of corrosion. CRST exhibits a corrosion rate less than half that of the other two steels. (The H specimens exhibited no corrosion, indicating problems in fabrication. Those tests are being repeated.)

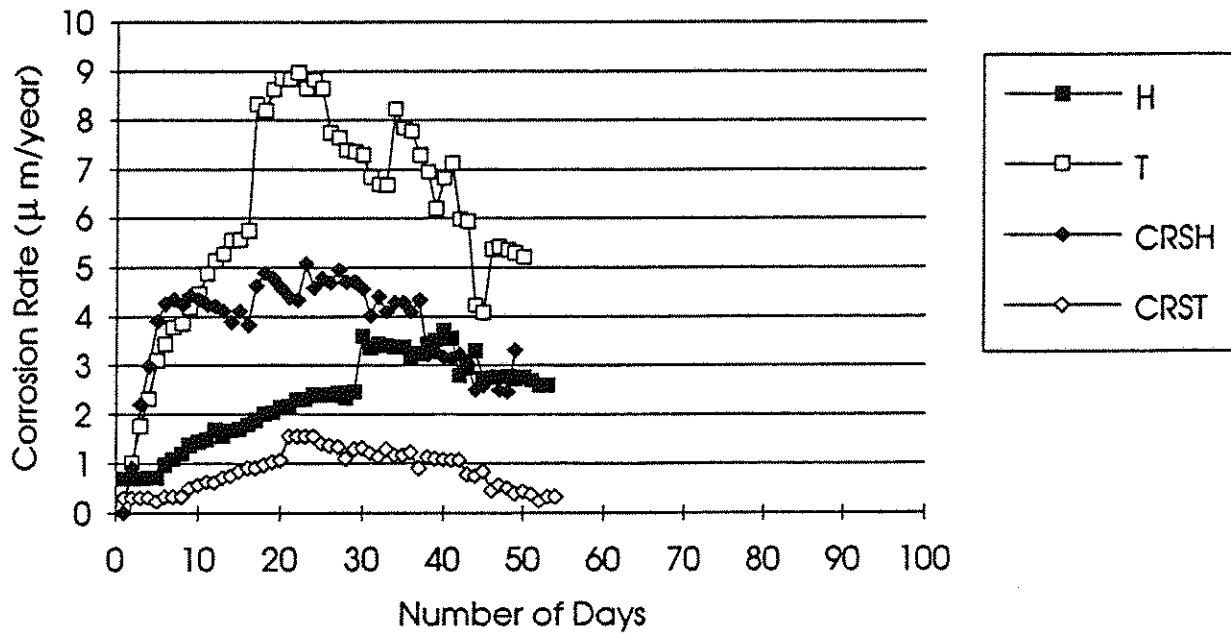


FIGURE 6 Corrosion rate versus time for macrocell test specimens subjected to a 1.6 m ion solution of NaCl (25.4 μm per year = 1 mil per year = 0.001 in. per year)

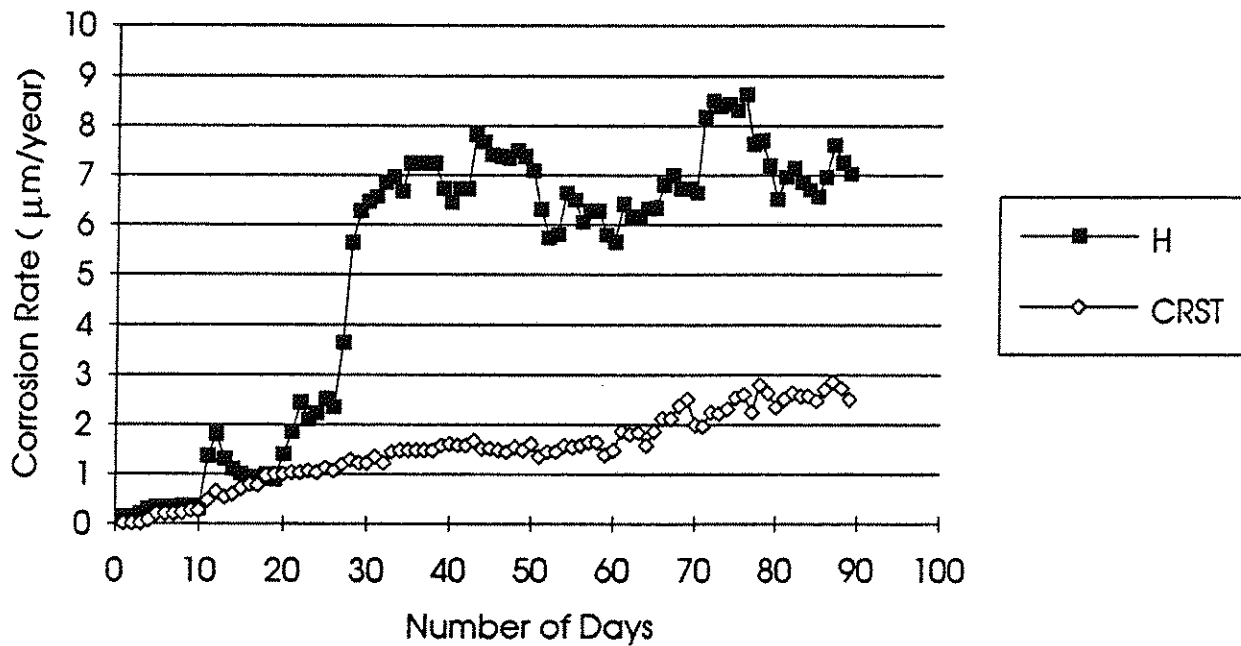


FIGURE 7 Corrosion rate versus time for macrocell test specimens subjected to a 6.4 m ion solution of NaCl (25.4 μm per year = 1 mil per year = 0.001 in. per year)

At a molal ion concentration of 1.6 (Figure 6), the T steel exhibits the highest corrosion rate, followed by CRSH, H, and CRST. Once again, the corrosion-resistant Thermex steel exhibits the lowest corrosion rate.

Finally, in Figure 7, the macrocell results for the H and CRST steels with a 6.4 molal ion concentration of NaCl

(equivalent to a 15 percent solution) are illustrated. At this high salt concentration, the CRST steel exhibits a corrosion rate less than 40 percent of that exhibited by the standard hot-rolled steel. The macrocell specimens made with the corrosion inhibitors (not shown) exhibit uniformly low corrosion rates.

In contrast to the macrocell tests, the rapid corrosion potential tests using a 15 percent sodium chloride solution have exhibited no real difference between the four types of steel. All four steel types reached a corrosion potential (note, no macrocell corrosion occurs in these tests) with respect to a standard calomel electrode between -0.5 and -0.6 volts, in most cases, within five days. The lack of difference in corrosion potential indicates that the nature of the difference in the corrosion resistance of CRST and the other steels may be tied to differences in the corrosion products and surface condition of the bars.

In the long-term tests, no clear difference in response is discernible during the first sixteen weeks of the study. Ultimately, however, the corrosion resistance of the new steel must be established based on the longer time-to-corrosion tests.

FINDINGS

Due to the nature of the test specimens and rate of corrosion, findings to date must be limited to those obtained from the small scale macrocell tests. In these tests, the CRST (corrosion-resistant heat treated) specimens have exhibited superior corrosion resistance compared to the other steels. The evidence suggests that the difference is based principally on the nature of the corrosion products and the surface properties of the CRST steel.

While the short-term tests are not, in themselves, adequate to justify the immediate application of the new corrosion resistant steel in full-scale structures, they do provide justification for continued study, with special emphasis on the results of the long-term tests. It also appears to be worthwhile to compare the corrosion resistance of the new steels to conventional steels when subjected to deicers other than sodium chloride, as proposed for Stage 2 of the project. In conjunction with the Stage 2 tests, it is proposed that the contractor be authorized to repeat any short-term tests that exhibit anomalies in the results, at no additional cost to the sponsors.

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