

**CORROSION-RESISTANT STEEL REINFORCING BARS
INITIAL TESTS**

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CORROSION-RESISTANT STEEL REINFORCING BARS - INITIAL TESTS

ABSTRACT

The initial portion of the first phase of a five phase research effort to evaluate a corrosion-resistant steel for reinforcing bars is described. Rapid corrosion potential and time-to-corrosion (macrocell) tests are used. The test specimen consists of a No. 5 reinforcing bar embedded in a 30 mm diameter, 102 mm long cylinder of mortar. The mortar is made using portland cement, graded Ottawa sand, and deionized water. Four different steel types are evaluated: hot-rolled regular steel, Thermex treated (quenched and tempered) regular steel, hot-rolled corrosion resistant steel, and Thermex treated corrosion resistant steel.

Corrosion potential tests are performed to determine the tendency of a steel to corrode. The results for these tests are fairly consistent, with little scatter. There is no significant difference in potentials for the four steels. The use of different test solutions did not influence the potential of the four steels.

The macrocell tests are performed to determine the time-to-corrosion and the corrosion rates. The results for some of these tests are not consistent and show considerable scatter. The macrocell test is sensitive to the quality in the specimen fabrication. Because the initial tests in Phase I did not perform as intended, it is difficult to determine for certain which steel has the best corrosion resistance based on the results reported here. However, the hot-rolled regular steel specimens consistently exhibit the highest corrosion rate.

The test solutions used at the anode and cathode in the macrocell tests appear to influence the corrosion rate and the difference in rates between the four steels. When the difference in pH of the anode and cathode solutions is decreased, the corrosion rates are reduced and the difference between the rates for the four steels is more pronounced.

Based on the results of the Phase I initial tests, some modifications to the specimen fabrication procedure are recommended. The epoxy band should be applied in two coats. The reinforcing bar lengths should be heated after cleaning and after applying each coat in order to improve the bond

between the reinforcing bar and the first epoxy coat as well as between the two coats of epoxy. Special care should be exercised when applying the epoxy band. Addition work in Phase I includes an evaluation of the effects of changing the ratio of the number of cathode to anode specimens from 3:3 to 2:1. Special care should also be exercised in the oversight of the corrosion potential and macrocell tests.

Key words: Chlorides; concrete; corrosion; corrosion testing; corrosion potentials; macrocells; reinforcing bars

INTRODUCTION

The deterioration of reinforced concrete structures is a major problem. The cost of repairing or replacing deteriorated structures has become a major liability for highway agencies, estimated to be more than \$20 billion and to be increasing at \$500 million a year. The primary cause of this deterioration is the corrosion of steel reinforcing bars due to chlorides. The two main sources of chlorides are deicing chemicals or marine exposure. The winter weather maintenance, bare pavement policies of many highway agencies have resulted in extensive usage of salt-based deicing chemicals. The most common chemical used has been NaCl.

Several measures have been developed and implemented to prevent the chloride-induced corrosion of steel reinforcing bars and the resulting deterioration. Some of the early measures used included lowering the water-cement ratio and increasing the cover over the steel reinforcing bars. Concrete permeability can be reduced by the use of admixtures. Corrosion inhibitors are also being used. The basic principle is to either prevent the chlorides from reaching the steel or increase the time needed to reach the steel. While these measures generally do not stop corrosion from eventually initiating, they do improve durability and increase the service life of reinforced concrete structures.

A new measure with potential to prevent deterioration of concrete structures due to the corrosion of steel reinforcing bars is a corrosion-resistant steel. It was developed by the Tata Steel Company in India, and involves two innovations: microalloying and heat treating the steel (Tata Steel 1991a, 1991b). The microalloying consists of adding small percentages of copper, chromium, and phosphorous to the steel. Initial studies conducted by Tata Steel indicated that a combined minimum of 0.9% by weight of the three elements is needed. Suggested maximum percentages by weight are 0.50% for copper, 0.80% for chromium, and 0.12% for phosphorous. The research done by Tata Steel also showed that, if the steel is quenched and tempered after the rolling process, the corrosion resistance is improved. The quenching and tempering is known as the Temcor or Thermex process.

Several corrosion resisting mechanisms contribute to make the new steel corrosion-resistant (Jha et al. 1992). The iron and chromium react to form a spinel oxide ($\text{FeO} \cdot \text{Cr}_2\text{O}_3$) which is a poor

conductor and acts to slow the rate of corrosion. In the presence of chlorides, a layer of copper chloride-copper hydroxide ($\text{CuCl}_2 \cdot 3\text{Cu}(\text{OH})_2$) is formed, which is less soluble than the corrosion products formed when chlorides react with conventional steel and therefore acts to retard corrosion. Phosphorous oxides are formed which serve as corrosion inhibitors. The corrosion products for the new steel, $\text{CuCl}_2 \cdot 3\text{Cu}(\text{OH})_2$ and $\text{FeO} \cdot \text{Cr}_2\text{O}_3$, form a compact dense layer that adheres to the steel reinforcing bar better than the corrosion products formed on conventional steel and reduces the amount of water and oxygen available at the uncorroded steel surface.

The corrosion of steel reinforcing bars is an electrochemical process that requires a flow of electric current and several chemical reactions. An adequate supply of water and oxygen is necessary for the chemical reactions. The rate of corrosion is dependent on the availability of oxygen and chloride ions, the ratio of steel surface area at the anode to that at the cathode, and the electrical resistivity of the concrete. The availability of oxygen is a function of its rate of diffusion through the concrete, which is affected by how saturated the concrete is with water. When totally submerged, the diffusion rate is slowed because the oxygen must diffuse through the pore water. When the concrete is dry, the oxygen can freely move through the empty pore spaces. Alternating wet/dry cycles allows oxygen to diffuse more readily. Wet concrete has a lower resistivity, and the hydroxyl ions needed for the electrolyte are present. Dry concrete has a higher resistivity. It also does not have the electrolytes needed.

Concrete is alkaline due to the presence of $\text{Ca}(\text{OH})_2$, KOH , and NaOH . Due to the high alkalinity, pH, of the concrete pore water, the steel reinforcing bars are passivated by an iron oxide film that protects the steel.

Chloride ions reach the reinforcing steel by penetrating the concrete via the pore water and through cracks in the concrete. The chloride ions dissolve the passive film by lowering the pH of the pore water and penetrate the passive film to react with iron to form a soluble iron-chloride complex (Fraczek 1987). When the iron-chloride complex diffuses away from the bar to an area with a higher pH and concentration of oxygen, it reacts with hydroxyl ions to form $\text{Fe}(\text{OH})_2$, which frees the chloride ions to continue the corrosion process, if the supply of available water and oxygen is

adequate (Dillard et al. 1993).

To initiate corrosion, several threshold levels for chlorides need to be exceeded. The ratio of chloride ions to the weight of cement needs to be greater than 0.4% and the concentration of chloride ions needs to be more than 0.71 kg/m³. The ratio of chloride to hydroxyl ions also needs to be greater than 0.6 (Dillard et al. 1993).

The distribution of chlorides in a reinforced concrete slab is not uniform. The chlorides typically enter the concrete from the top surface. The top mat of reinforcing steel is then exposed to higher concentrations of chlorides. The chlorides shift the potential of the top mat to a more negative (anodic) value. Since the potential of the bottom mat has a more positive (cathodic) value, the resulting difference in potentials sets up a galvanic type corrosion cell called a macrocell. An electric circuit is established. The concrete serves as the electrolyte and wire ties, metal chair supports, and steel bars serve as metallic conductors.

The corrosion products resulting from the corrosion of steel reinforcing bars occupy a volume equal to three to four times the volume of the original steel. This increase in volume induces stresses in the concrete that result in cracks, delaminations, and spalls. This accelerates the corrosion process by providing an easy pathway for the water and chlorides to reach the steel.

Tests performed by Tata Steel established that the new steel has improved corrosion resistance in the atmosphere, i.e. the bars were not in contact with concrete. Only one series of tests with the steel embedded in concrete were performed. The test consisted of submerging a concrete block containing a single bar in salt water. This is not a recognized test procedure in the United States. The evaluation of a single bar is also not a true representation of the corrosion resistant properties of a steel, since it does not model the formation of a macrocell. Although the new steel has improved corrosion resistance in the atmosphere, it may or may not have improved corrosion resistance when in contact with concrete. This is because some metals perform differently when exposed to different environments. Therefore, there is a need to thoroughly evaluate the corrosion resistance of the new steel when embedded in concrete.

This report describes the initial effort in the first phase of a study to evaluate the corrosion

resistance of the new steel. The study is being carried out in five overlapping phases. In Phase I, the evaluation of the corrosion resistant steel is done through the use of rapid tests: rapid corrosion potential tests and rapid time-to-corrosion (macrocell) tests. The rapid tests are procedures that were developed at the University of Kansas as part of the Strategic Highway Research Program to evaluate the effects of deicing chemicals on steel reinforcing bars in a relatively short time (Martinez et al. 1990). Using the tests, the reinforcing bars can be evaluated in environments that simulate the environment in an actual concrete structure. The tests allow a large number of variables to be evaluated in three months or less, as compared to one year for more conventional tests.

Four steel "types" were evaluated. These four types represent the possible combinations of two alloys and two heat treatment processes. The two types of alloys are the regular reinforcing steel currently used in reinforced concrete construction and the microalloyed steel used for the new corrosion resistant steel. The reinforcing steel is hot-rolled without any heat treatment or is heat treated using the Thermex process. The hot-rolled regular reinforcing steel is denoted by H, the Thermex treated regular reinforcing steel is denoted by T, the hot-rolled corrosion resistant reinforcing steel is denoted by CRSH, and the Thermex treated corrosion resistant reinforcing steel is denoted by CRST.

The remaining efforts in the study include the completion of Phase I and the execution of the other four phases: the bench scale time-to-corrosion tests, an evaluation of the effects of deicer type and concentration, mechanical property tests, and data analysis. The bench scale tests are the southern exposure and cracked beam tests. Additional corrosion potential and macrocell test are being performed to evaluate the effects of different concentrations of NaCl and the effects of different deicers. The influence of the microalloying process on the mechanical properties (yield strength, tensile strength, elongation, and bendability) of the corrosion-resistant steel will be evaluated. Some macrocell tests were added to evaluate the effects of changing the ratio of anode to cathode specimens. Because of erratic results from the macrocell tests done in Phase I and because a visual examination of the reinforcing bars after the conclusion of the test period confirmed suspicions that the tests were not performing as intended, some retests of the Phase I macrocell tests

were added, and some modifications were made to the specimen fabrication procedure.

EXPERIMENTAL WORK

Test specimen

The corrosion resistance of the four types of steels is evaluated using a "lollipop" test specimen (Fig. 1). It consists of a 127 mm length of steel reinforcing bar embedded 76 mm in a mortar cylinder. The length of the mortar cylinder is 102 mm. The overall specimen length is 152 mm. The specimen configuration is based on the specimen used in a study to develop a rapid test for determining the effects of deicing chemicals on the corrosion behavior of steel reinforcing bars in concrete (Martinez et al. 1990).

The specimen mold (Fig. 2) is made up of PVC pipe and fittings. Laboratory grade rubber stoppers are used to hold the reinforcing bars in place and maintain uniform cover. The specimen fabrication fixture consists of two pieces of 2 x 8 CCA pressure treated lumber. Holes and recesses are bored into the flat surfaces to accept the specimen mold assembly and facilitate mortar placement. Threaded steel rods with nuts and wingnuts are used to clamp the specimen molds in the fixture. Tension in the rods is adjusted to hold the PVC mold together and apply sufficient pressure to the rubber stoppers to prevent the bars from moving. Each fixture can accept eight specimen assemblies and two fixtures are used. This allows the fabrication of 16 specimens at one time.

Specimen preparation starts with cutting 127 mm length sections of steel reinforcing bar. One end of each section is drilled and tapped to provide for an electrical connection. The bar is then cleaned with acetone to remove dirt and grease. A 15 mm wide epoxy band is applied around the bar 51 mm from the tapped end. This epoxy band is used to prevent crevice corrosion at the interface between the steel bar and the mortar and to ensure that corrosion occurs on the portion of the bar that is embedded in the mortar cylinder. The epoxy is mixed and applied according to the manufacturer's instructions.

The completed bar and mold assembly is illustrated in Fig. 2. Assembly into the mold is accomplished in several steps. The first step consists of inserting the tapped end of the bar into the

small stopper (A) so that the wider end is centered on the epoxy band. This rubber stopper is then inserted into the machined PVC connector (B), with the wider end of the stopper in contact with a small ridge located on the inside surface of the connector. The large rubber stopper (C) is placed in the end of the large connector (D) that has the larger inside diameter. The wider end of the stopper is placed flush with the end of the connector. The connector containing the rubber stopper and bar assembly is then placed into the other end of the large connector. The tapped end of the bar is inserted into the large rubber stopper. The section of PVC pipe (E) is then placed into the other end of this assembly.

Modifications are needed for several of the components to facilitate assembly and disassembly. The holes in the rubber stoppers must be enlarged to accommodate the reinforcing bar, and the PVC pipe is slit to ease removal of the completed specimen. The pipe is taped closed prior to assembly.

The completed mold assembly is then inserted into the recesses in the top and bottom wooden pieces (F) of the fixture. The entire fixture assembly is tightened by using the wingnuts and the threaded rods (G). The tension in the rods is adjusted to control the position of the bar.

Materials

Reinforcing steel - Four different types of reinforcing steel are used. The hot-rolled regular reinforcing steel meets the requirements for ASTM A 615 Grade 40 reinforcement. The Thermex treated regular reinforcing steel is quenched and tempered immediately after the rolling process is completed and meets the requirements for ASTM A 615 Grade 60 reinforcement. The corrosion resistant reinforcing steels contain small percentages of copper, chromium, and phosphorous. The Thermex treated corrosion resistant steel is quenched and tempered immediately after the rolling process and the hot-rolled corrosion resistant steel is not.

The recommended, actual, and allowable percentages for the three microalloying elements in the corrosion resistant steel are summarized in Table 1. The microalloying does not meet the current ASTM A 615 specification because the recommended maximum percentage of phosphorous for the corrosion-resistant steel, 0.12%, exceeds the maximum percentage presently allowed in conventional reinforcing steel, 0.06%. The current ASTM A 615 specification does not restrict the

amount of copper and chromium.

The actual amounts of the three alloying elements in the heat of corrosion-resistant steel used for the Phase I bars are documented in a March 9, 1994 Chemical and Physical Test Report provided by the Florida Steel Corporation and are less than the maximums recommended by Tata Steel. The amount of copper is close to the recommended maximum, 0.44% compared to 0.50%. The amounts of chromium and phosphorous are significantly less than the recommended maximums, 0.53% compared to 0.80% for chromium, and 0.08% compared to 0.12% for phosphorous.

Mortar - The mortar was made with Type I portland cement and graded Ottawa sand meeting the requirements of ASTM C 778. The mortar was proportioned to have a water-cement ratio of 0.5 and a sand to cement ratio of 2.0 by weight. These proportions were chosen to represent the mortar constituent of a 4000 psi concrete mix.

Epoxy - The liquid epoxy coating used was Scotchkote 306 manufactured by the 3M Company.

Water - Deionized water was used to minimize the effect of any impurities in tap water, primarily chlorides.

Specimen fabrication

The mortar was mixed by hand and placed in the specimen mold in three layers. Each layer was rodded 25 times with a 300 mm long, 3 mm diameter "mini" rod made from a coat/pants hanger and vibrated for 15 seconds on vibrating table at a frequency of 60 Hz and an amplitude of 0.15 mm. The specimens were initially cured by covering the PVC molds and the wood fixture with water saturated towels. After 24 hours, the PVC molds were taken out of the fixtures and disassembled. The specimens were then cured for 13 days in saturated lime water. After curing for a total of 14 days, the bars were in a passive (non-corroding) condition.

Test procedures

Two tests, the corrosion potential and macrocell tests, were performed. Both are rapid corrosion tests and were performed to evaluate the corrosion resistance of the four steels.

The corrosion potential test was performed to determine the relative tendency of the steels

to corrode. A schematic of the test configuration is shown in Fig. 3. Two plastic containers were used in the test. In one container, a single specimen was exposed to either a deicer or a simulated pore solution. A saturated calomel reference electrode was placed in a concentrated KCl solution (15 g of KCl per 100 cc of water) in the other container. A salt bridge was placed between the two containers to provide for an ionic path. Both containers were sealed to prevent evaporation and carbon dioxide from affecting the pore solution. Holes were provided in the container lids for the wire from the test specimen, the salt bridge, and the wire from saturated calomel electrode.

The time-to-corrosion or macrocell test was performed to determine the time to initiation of corrosion and the corrosion rate of the steels. A schematic of the test configuration is shown in Fig. 4. Two plastic containers were used: one for the anode and one for the cathode. Three specimens were placed in each container along with mortar fill. One set of specimens served as the cathode and was exposed to a pore solution. The other set of specimens served as the anode and was exposed to a deicer solution. A salt bridge was used to provide an ionic path between the two containers. Both containers were sealed for the same reasons as for the potential tests. The three specimens were positioned to maintain at least 25 mm clearance between them. The specimens were wired in parallel. To provide oxygen to the cathode, compressed air was bubbled through a saturated solution of NaOH to remove CO₂ to prevent carbonation. Water was added as needed to compensate for evaporation. Holes were provided in the container lids for the wires from the test specimens, the salt bridge, and the oxygen supply. The specimens in the two containers were electrically connected across a 10 ohm resistor.

In both tests, five litre plastic containers were used to hold the test specimens, mortar fill, deicers, pore solutions, and saturated KCl solutions. Pore solution was used to simulate the environment found in hardened concrete. A mortar fill was used as a buffer and to simulate the relative amount of cementitious material in an actual concrete structure. The mortar fill used the same mortar mixture as the specimens. The fill was cast in 19 mm metal cookie sheets at the same time as the specimens. The mortar sheets were broken into pieces of 19 to 38 mm nominal size prior to use.

Salt bridges were used to make an ionic path between containers. The procedure for making the salt bridges is described by Martinez et al. (1990). The materials used to make four 900 mm long salt bridges consist of 4.5 g of agar, 30 g of potassium chloride (KCl), 100 ml of distilled water, and 3.6 m of plastic tubing with an inside diameter of 5 mm. The agar and KCl were first dissolved in the distilled water. The mixture was then poured into sections of the tubing, and the filled sections were immersed in boiling water for 20 minutes or until the mixture gels. The completed salt bridges were then cooled prior to use. The gel in the tubing needs to be continuous, without air bubbles, for an ionic path to be established and maintained.

The composition of the deicer and pore solutions used are summarized in Table 2. The chemical composition of the pore solution is based on that used by Martinez et al. (1990). The pore solution used consists of 18.81 g of KOH and 18.87 g of NaOH per litre of deionized water. Due to an error in preparing the pore solution, the first macrocell tests were performed with pore solutions deficient in the amount of NaOH. Only 8.87 g of NaOH was used, compared to the 18.87 g that should have been used. This error was detected and corrected shortly after the macrocell tests started.

The deicer used in the Phase I evaluation is NaCl. Laboratory grade NaCl was used initially. Shortly after the tests were started, a commercial grade of NaCl was substituted for the laboratory grade. The commercial grade was considered to be pure enough. The test concentration was set at 15% by weight which provides a 6.04 molal ion concentration. The molal ion concentration is important in that the ice melting capacity of a deicer is controlled by the ion concentration. Expressing the concentration in this way allows different deicers to be compared using a common frame of reference. The 6.04 m ion deicer concentration was made using 176.5 g of NaCl per liter of water. A 6.04 m ion concentration of deicer in a simulated pore solution consisted of 18.81 g of KOH and 18.87 g of NaOH along with 176.5 g of NaCl per litre of deionized water.

After 14 days of curing, the specimens were removed from the saturated lime water. Compressed air was used to thoroughly dry the tapped end of the bar. A 16 AWG wire was connected to the bar with a screw placed in the tapped end of the bar. The connection was then

covered with epoxy to prevent corrosion from occurring at the connection point. The test specimens were placed bar end up in a container and fill material was added. The specimens were positioned in the containers so that the top of the mortar cylinders remained 25 mm above the surface of the deicer or pore solution. This was done to prevent solutions from entering the specimen from the top at the interface between the epoxy band and the mortar.

Corrosion potential tests - The corrosion potential tests were run for 40 days, with voltages between the specimen and the reference electrode measured daily. The readings constitute the corrosion potential for the steel being tested in a specific deicer or pore solution.

The corrosion potential tests were performed under three different test conditions, which are summarized in Table 3. In test condition A, the specimens were exposed to a 6.04 m ion (15%) NaCl solution. In test condition B, the specimens were exposed to a 6.04 m ion (15%) concentration of NaCl in a simulated pore solution. In test condition C, the specimens were exposed to a simulated pore solution.

Macrocell tests - The macrocell tests were run for 100 days. The voltage drop across the 10 ohm resistor was measured and recorded on a daily basis. The measured voltage drop and the actual resistance of the resistor were used to calculate the corrosion current. The corrosion current and the area of the anode are used to calculate a corrosion rate based on Faraday's Law (Jones 1992).

The macrocell tests were performed under three different test conditions which are summarized in Table 4. In test condition A, the cathode specimens were exposed to a simulated pore solution that was deficient in the amount of NaOH, and the anode specimens were exposed to a 6.04 m ion (15%) NaCl solution. In test condition B, the cathode specimens were exposed to a simulated pore solution, and the anode specimens were exposed to a 6.04 m ion (15%) NaCl solution. In test condition C, the cathode specimens were exposed to the simulated pore solution, and the anode specimens were exposed to a 6.04 m ion (15%) concentration of NaCl in simulated pore solution.

RESULTS AND EVALUATION

The combination of the high water-cement ratio of the mortar, 0.5, the low mortar cover over the reinforcing bar, 7 mm, and the deicer concentration used, 6.04 m ion concentration of NaCl, creates an environment at the steel surface that is significantly more corrosive than in most reinforced concrete structures. In addition, the high concentration of chlorides at the steel surface is reached in a relatively short time, 1 to 3 days. As a result, the potentials and corrosion rates determined in these tests are not representative of those that would occur in a typical structure exposed to deicing chemicals or a marine environment.

Corrosion potential tests

The results of the corrosion potential tests are illustrated in Figs. 5 through 20. The tests started immediately after the end of the 14 day curing period. The corrosion potentials are all given with respect to a saturated calomel electrode.

The results for the H, T, CRSH, and CRST specimens exposed to a 6.04 m ion concentration of NaCl, test condition A, are illustrated in Figs. 5 through 8. At the end of 40 days, the potentials for the H specimens are between -0.550 and -0.600 volts, the potentials for the T specimens are all about -0.575 volts, the potentials for the CRSH specimens are between -0.500 and -0.575 volts, and the potentials for the CRST specimens are between -0.525 and -0.575 volts. A considerable amount of scatter is present in the data for the CRSH and CRST specimens.

The average corrosion potentials for the four steels when exposed to test condition A are illustrated in Fig. 9. There does not appear to be any significant difference in the average corrosion potentials for the four steels.

The results for the H and CRST specimens exposed to a 6.04 m ion concentration of NaCl in a simulated pore solution, test condition B, are illustrated in Figs. 10 and 11, respectively. At the end of 40 days, the potentials are about -0.525 volts for the H specimens and are between -0.400 and -0.575 volts for the CRST specimens.

The average corrosion potentials for the two steels exposed to test condition B are illustrated in Fig. 12. During the initial stages of the tests, the H specimens exhibited a more positive potential

than the CRST specimens. However, near the end of the tests, the corrosion potential of the H specimens shifted dramatically. This resulted in the CRST specimens having a slightly more positive potential at the end of 40 days.

The results for the T, CRSH, and CRST specimens exposed to a simulated pore solution, test condition C, are illustrated in Figs. 13 through 15. This test condition was used to evaluate the corrosion potential of the specimens in a noncorrosive environment. At the end of 40 days the potentials for the T specimens are about -0.450 volts, the potentials for the CRSH specimens are between -0.225 and -0.275 volts, and the potentials for the CRST specimens are about -0.475 volts.

The average corrosion potentials for the three steels exposed to test condition C are illustrated in Fig. 16. The T and CRST specimens have about the same potential, with the CRSH specimens having a more positive potential for the entire 40 day test period.

The average corrosion potentials for H specimens exposed to a 6.04 m ion concentration of NaCl and a 6.04 m ion concentration of NaCl in simulated pore solution are compared in Fig. 17. The specimens exposed to the NaCl in simulated pore solution have a less negative potential than those specimens exposed to the NaCl alone.

The average corrosion potentials for T specimens exposed to a 6.04 m ion concentration of NaCl and a simulated pore solution are compared in Fig. 18. The specimens exposed to a simulated pore solution have a less negative potential than those specimens exposed to the NaCl in a simulated pore solution.

The average corrosion potentials for CRSH specimens exposed to a 6.04 m ion concentration of NaCl and a simulated pore solution are compared in Fig. 19. Once again the specimens exposed to the simulated pore solution have a less negative potential than those specimens exposed to the NaCl in simulated pore solution.

The average corrosion potentials for CRST specimens exposed to a 6.04 m ion concentration of NaCl, a 6.04 m ion concentration of NaCl in a simulated pore solution, and a simulated pore solution are compared in Fig. 20. In this case, the specimens exposed to the simulated pore solution have a less negative potential than those specimens exposed to NaCl in simulated pore solution,

which, in turn, have a less negative potential than those specimens exposed to only NaCl.

Macrocell tests

The results of the macrocell tests are illustrated in Figs. 21 through 37. As with the corrosion potential tests, the macrocell tests started immediately after the end of the 14 day curing period. The corrosion rates are given in μm per year ($25.4 \mu\text{m}$ per year = 0.001 in. per year).

The results for the H, T, CRSH, and CRST specimens exposed to a simulated pore solution that was deficient in the amount of NaOH at the cathode and a 6.04 m ion concentration of NaCl at the anode, test condition A, are illustrated in Figs. 21 through 24. For the H specimens, the corrosion rate at the end of 100 days is 12 to 14 μm per year. For the T specimens, the corrosion rate at the end of 100 days is 10 to 12 μm per year. For the CRSH specimens, the corrosion rates for the two specimens at the end of 100 days are significantly different. One specimen has a rate of about 5 μm per year, while the other specimen has a rate of about 16 μm per year, more than three times as much. For the CRST specimens, the corrosion rate at the end of 100 days is 11 to 15 μm per year.

The average corrosion rates for the four steels subjected to test condition A are illustrated in Fig. 25. For this particular test configuration the CRSH specimens exhibit the lowest corrosion rate. The T specimens exhibit the next lowest rate followed by the CRST specimens. The H specimens exhibit the highest corrosion rate. However, the difference in the average corrosion rates for the four steels does not appear to be significant.

The results for H, T, CRSH, and CRST specimens exposed to a simulated pore solution at the cathode and a 6.04 m ion concentration of NaCl at the anode, test condition B, are illustrated in Figs. 26 through 29. For the H specimens, the corrosion rate at the end of 100 days ranges between 15 and 20 μm per year. For the T specimens, the corrosion rate at the end of 100 days is between 10 and 12 μm per year. For the CRSH specimens, the corrosion rate at the end of 100 days is between 14 and 16 μm per year. For the CRST specimens, the rates the rates for the two specimens at the end of 100 days are somewhat different. For one specimen, the rate is about 11 μm per year, while for the other specimen, the rate is slightly higher, at 15 to 16 μm per year.

The average corrosion rates for the four steels exposed to test condition B are illustrated in

Fig. 30. For this particular test configuration the T specimens exhibit the lowest corrosion rate. The CRST specimens exhibit the next lowest rate followed by the CRSH specimens. The H specimens once again exhibit the highest corrosion rate. The difference in average corrosion rates is more pronounced.

The results for H and CRST specimens exposed to a simulated pore solution at the cathode and a 6.04 m ion concentration of NaCl in simulated pore solution at the anode, test condition C, are illustrated in Figs. 31 and 32. The rates for the two H specimens are significantly different. The rate for one of the specimens is highly erratic and ranges from essentially no corrosion to as high as 21 μm per year during the course of the test. The rate for the other specimen is more consistent, with the corrosion rate at the end of 100 days between 12 and 14 μm per year. The rates for the two CRST specimens are somewhat different. For one specimen, the rate is about 3 μm per year, while for the other specimen, the rate is 8 to 10 μm per year, about three times as much.

The average corrosion rates for the two steels subjected to test condition C are illustrated in Fig. 33. In general, the CRST specimens exhibit a lower corrosion rate than the H specimens.

The average corrosion rates for H specimens exposed to a simulated pore solution that is deficient in the amount of NaOH at the cathode and a 6.04 m ion concentration of NaCl at the anode, test condition A; a simulated pore solution at the cathode and a 6.04 m ion concentration of NaCl at the anode, test condition B; and a simulated pore solution at the cathode and a 6.04 m ion concentration of NaCl in a simulated pore solution at the anode, test condition C, are compared in Fig. 34. In general, the specimens exposed to test condition C exhibit the lowest corrosion rate. The specimens exposed to test condition A exhibit the next lowest corrosion rate. The specimens exposed to test condition B exhibit the highest corrosion rate. Although the results for test condition C are fairly erratic, there is enough difference in the average corrosion rates to be able to make a comparison.

The average corrosion rates for T specimens exposed to a simulated pore solution that is deficient in the amount of NaOH at the cathode and a 6.04 m ion concentration of NaCl at the anode, test condition A, and a simulated pore solution at the cathode and a 6.04 m ion concentration of NaCl

at the anode, test condition B, are compared in Fig. 35. The specimens exposed to test condition B appear to have the lower average corrosion rate. However, the results are somewhat erratic with no significant difference between the two test conditions.

The average corrosion rates for CRSH specimens exposed to a simulated pore solution that is deficient in the amount of NaOH at the cathode and a 6.04 m ion concentration of NaCl at the anode, test condition A, and a simulated pore solution at the cathode and a 6.04 m ion concentration of NaCl at the anode, test condition B, are compared in Fig. 36. Once again the specimens exposed to test condition B appear to have the lower average corrosion rate. Although the results are somewhat erratic, the difference between the two test conditions is fairly constant.

The average corrosion rates for CRST specimens exposed to a simulated pore solution that is deficient in the amount of NaOH at the cathode and a 6.04 m ion concentration of NaCl at the anode, test condition A; a simulated pore solution at the cathode and a 6.04 m ion concentration of NaCl at the anode, test condition B; and a simulated pore solution at the cathode and a 6.04 m ion concentration of NaCl in simulated pore solution at the anode, test condition C, are compared in Fig. 37. The specimens exposed to test condition C exhibit the lowest corrosion rate. Although the specimens exposed to test conditions A and B are too close to accurately determine which have the higher rate, the corrosion rate for both conditions is higher than for test condition C.

Although the erratic results for some of the specimens make it difficult to be certain, it appears that differences in solutions at the anode and cathode influence the corrosion rates. When the difference in pH of the solutions decreases, the corrosion rates are lower and the difference in corrosion rates for the four steels is reduced. Since the cathode solution for test condition A does not contain as much NaOH as the cathode solution for test condition B and the anode solution for both test conditions is the same, a larger difference in pH results for test condition B. The corrosion rates for test condition B are generally higher and have a more pronounced difference in rates for the four steels. In test condition C, a simulated pore solution is added to the anode solution. As a result of this addition, the difference in pH is less than test conditions A and B and the corrosion rates for test condition C are lower.

Evaluation of Specimen Fabrication

The results of many of the macrocell tests are highly erratic, with an excessive amount of scatter in the test data. This led to a close visual examination of the steel reinforcing bars after the conclusion of the tests. The visual inspection consisted of dismantling the test set up and physically removing the mortar from the steel reinforcing bars. The examination revealed that the macrocell tests were not performing as intended. Instead of corrosion taking place on the portion of the steel reinforcing bar embedded in the mortar cylinder, corrosion was taking place underneath the epoxy band.

As a result of this finding, some revisions were instituted in the specimen fabrication procedure for the specimens that follow those described in this report. A different liquid epoxy coating was used (Morton Powder Coatings). The epoxy was also applied in two coats. After each coat was applied, the specimens were heated in an oven for 24 hours to bake the coating onto the bar and improve the bond between the coating and the bar, as well as between the two coats. The results obtained with the improved fabrication procedure will be presented in a later report.

SUMMARY AND CONCLUSIONS

This report describes the initial efforts in the first phase of a five phase study to evaluate a corrosion-resistant steel for reinforcing bars. Rapid corrosion potential and rapid time-to-corrosion (macrocell) tests are used. The test specimen consists of a No. 5 reinforcing bar embedded in a 30 mm diameter, 102 mm long cylinder of mortar. The mortar is made using portland cement, graded Ottawa sand, and deionized water. Four different steel types are evaluated: a hot rolled regular steel, H, a Thermex treated (quenched and tempered) regular steel, T, a hot-rolled corrosion resistant steel, CRSH, and a Thermex treated corrosion resistant steel, CRST.

Corrosion potential tests are performed to determine the tendency of a steel to corrode. The results for these tests are fairly consistent, with little scatter. There is no significant difference in potentials for the four steels. The use of different test solutions did not influence the potential of any of the four steels.

The macrocell tests are performed to determine the time-to-corrosion and the corrosion rates. The results for some of these tests are not consistent and show considerable scatter. The macrocell test is sensitive to the quality of specimen fabrication. The macrocell tests did not perform as intended; most of the corrosion occurred under the epoxy band and not on the portion of the steel bar embedded in the mortar. Therefore, it is difficult to determine for certain which steel has the best corrosion resistance. However, the H specimens consistently exhibited the highest corrosion rate.

The test solutions used at the anode and cathode in the macrocell tests appear to influence the corrosion rate and the difference between the rates for the four steels. When the difference in pH of the anode and cathode solutions is decreased, the corrosion rates are reduced and the difference between the rates for the four steels is more pronounced. Specimens exposed to a simulated pore solution at the cathode and a 6.04 m NaCl concentration in a simulated pore solution at the anode generally have the lowest corrosion rates, while specimens exposed to a simulated pore solution at the cathode and a 6.04 m NaCl solution at the anode have the highest corrosion rates.

Both the potential and macrocell tests use a 6.04 m concentration of NaCl in the deicer solution, a high water-cement ratio of the mortar, 0.50, and a low mortar cover over the reinforcing bar, 7 mm. As a result, a high concentration of chlorides at the steel surface is reached in a relatively short time, 1 to 3 days. This creates an environment at the steel surface that is significantly more corrosive than in an actual reinforced concrete structure throughout its service life. Therefore, the potentials and corrosion rates determined in these tests are not representative of those that would occur in a typical structure exposed to deicing chemicals or a marine environment.

FUTURE WORK

As discussed in previous sections, this report describes the initial portion of the first phase of a five phase study to evaluate a corrosion-resistant steel for reinforcing bars. The results for the balance of the study will be presented in later reports. The remaining work includes completion of Phase I, along with bench scale tests, potential and macrocell tests to evaluate the effect of different deicers and deicer concentrations, and mechanical property tests. The additional work in Phase I

includes an evaluation of the effects of changing the ratio of the number of cathode to anode specimens from 3:3 to 2:1.

Although some refinements have been made to the specimen fabrication procedures, further enhancements may be possible. Special care should be exercised in the application of the epoxy band. Some enhancements to the specimen curing procedure may also be possible. These items should be pursued in a future study. Special care should also be exercised in the oversight of the corrosion potential and macrocell tests.

The actual amounts of phosphorous and chromium in the corrosion-resistant steel are significantly less than the maximums recommended by Tata Steel (1991a, 1991b). Future work should investigate the corrosion resistance of steel reinforcing bars made with phosphorous and chromium alloying levels at or near the recommended maximums.

ACKNOWLEDGEMENTS

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Table 1. Summary of corrosion-resistant steel chemistry

Element	Recommended Maximum Percentage	ASTM A 615 Allowable Percentage	Actual Percentage
Copper	0.50	NA	0.44
Chromium	0.80	NA	0.53
Phosphorous	0.12	0.06	0.08

Table 2. Quantities of chemicals in test solutions in grams per liter of deionized water

Chemical	Test Solution			
	Deficient Pore Solution	Pore Solution	6.04 m (15%) NaCl Solution	6.04 m (15%) NaCl in Simulated Pore Solution
NaCl	0	0	176.5	176.5
KOH	18.81	18.81	0	18.81
NaOH	7.87*	17.87	0	17.87

* Insufficient amount of NaOH used in error

Table 3. Summary of potential test conditions

Test	Solution	Steels Evaluated
A	6.04 m (15%) NaCl Solution	H, T, CRSH, CRST
B	6.04 m (15%) NaCl in Simulated Pore Solution	H, CRST
C	Pore Solution	T, CRSH, CRST

Table 4. Summary of macrocell test conditions

Test	Cathode Solution	Anode Solution	Steels Evaluated
A	Deficient Pore Solution	6.04 m ion (15%) NaCl Solution	H, T, CRSH, CRST
B	Pore Solution	6.04 m ion (15%) NaCl Solution	H, T, CRSH, CRST
C	Pore Solution	6.04 m ion (15%) NaCl in Simulated Pore Solution	H, CRST

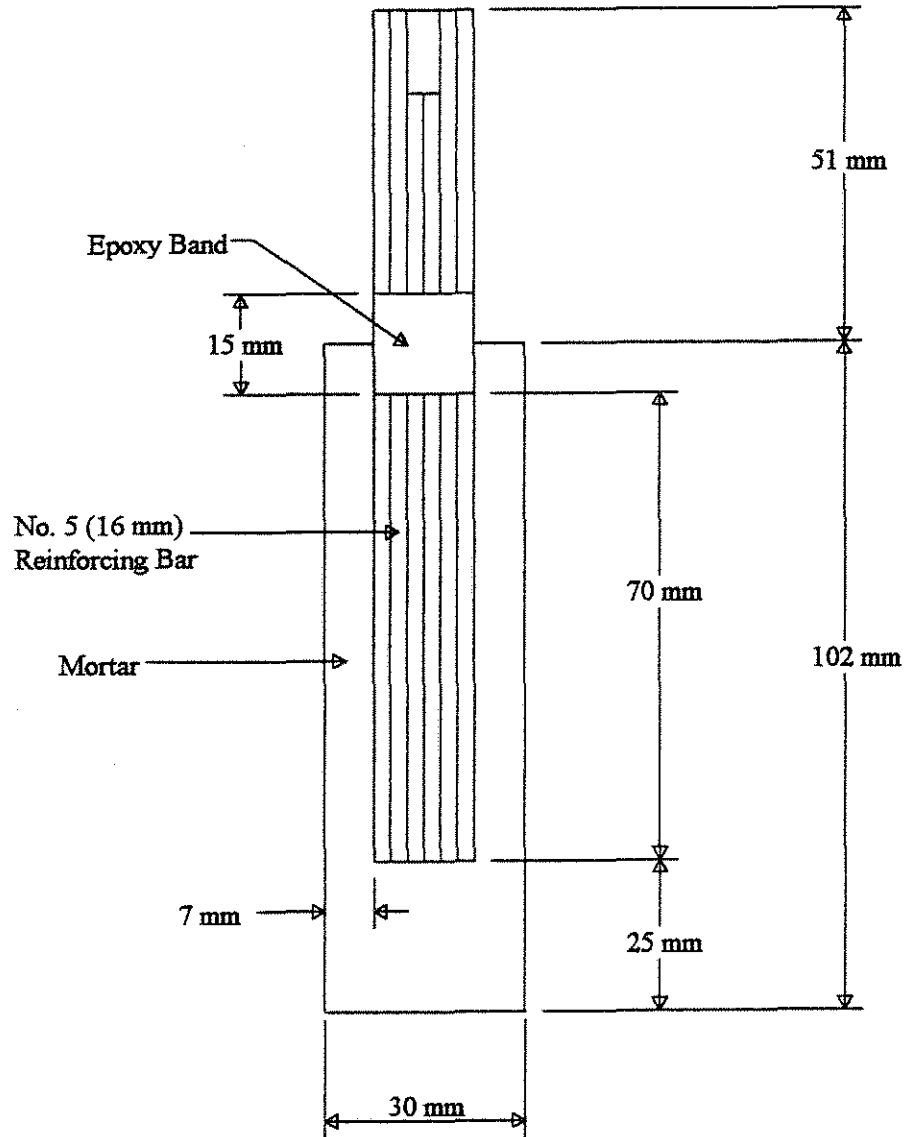


Fig. 1 Cross section of test specimen

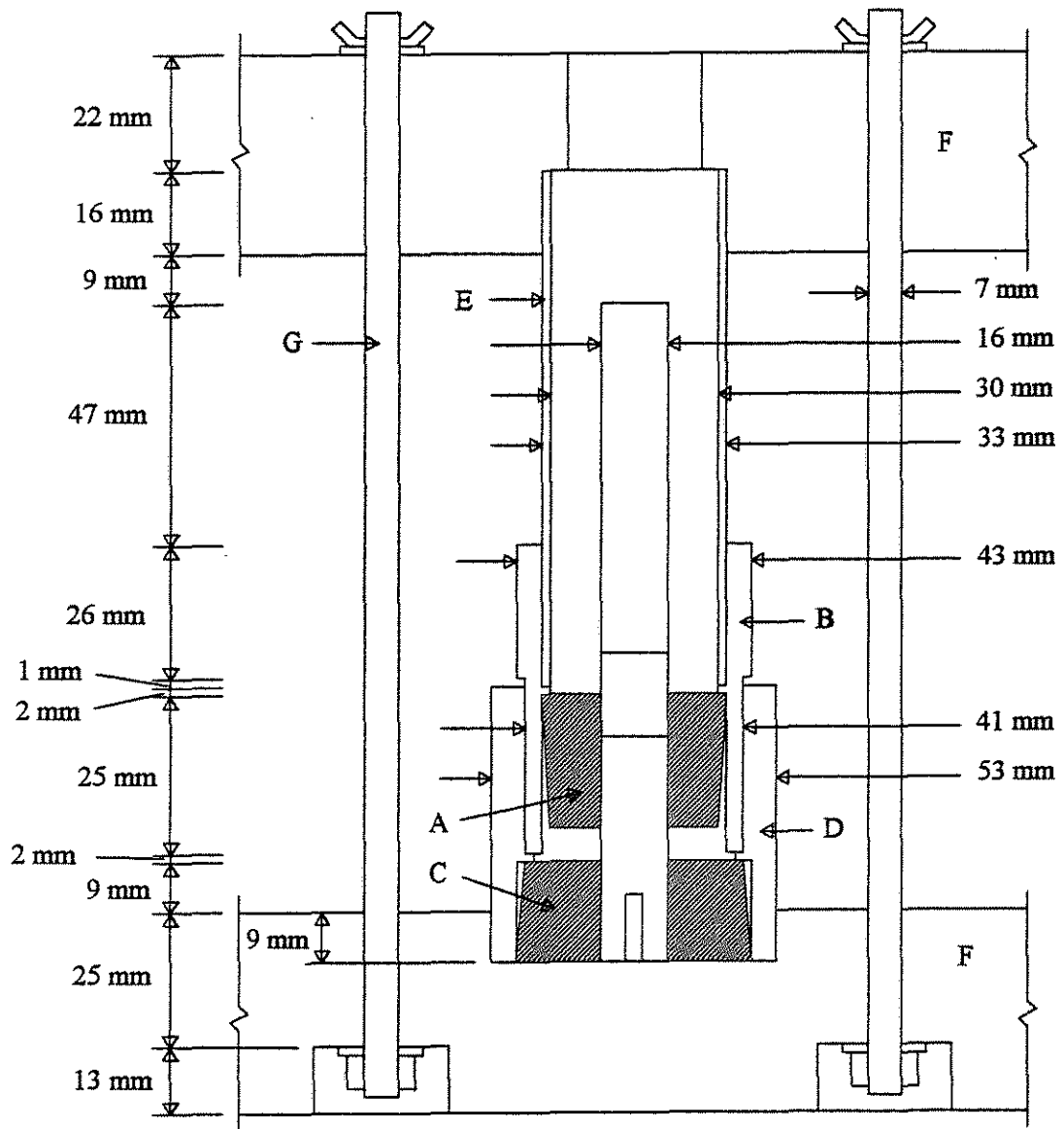


Fig. 2 Cross section of mold for test specimen

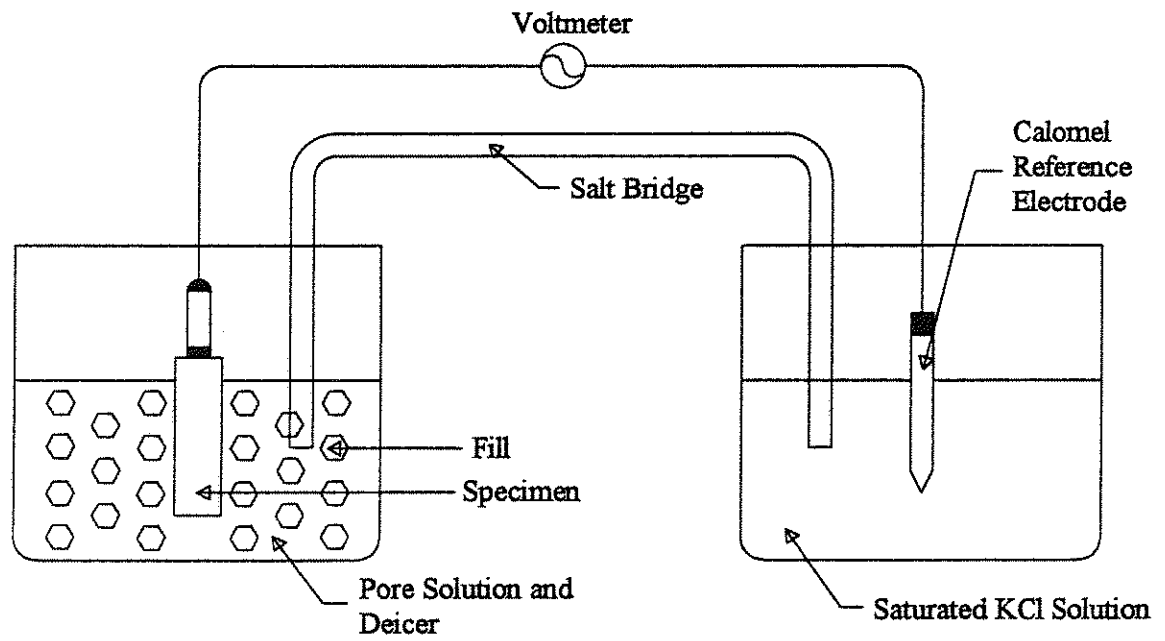


Fig. 3 Schematic of corrosion potential test configuration

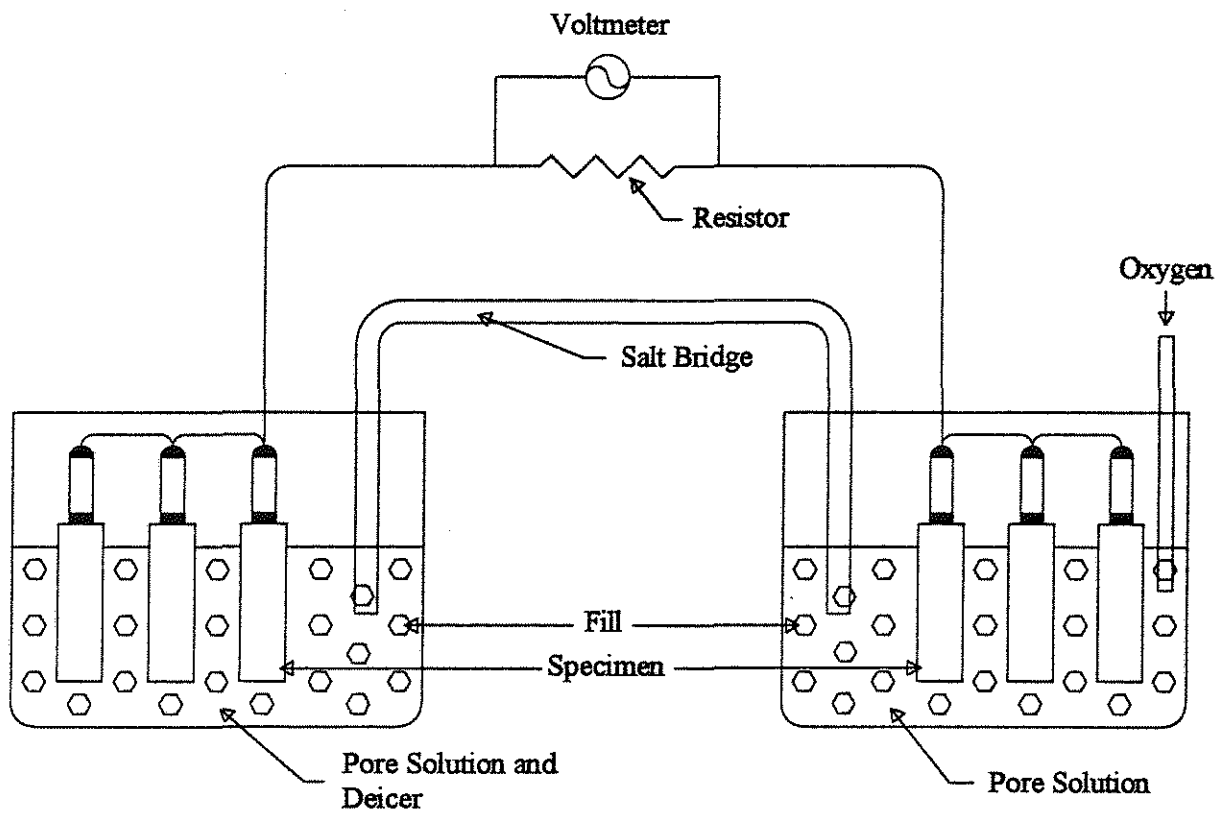


Fig. 4 Schematic of macrocell test configuration

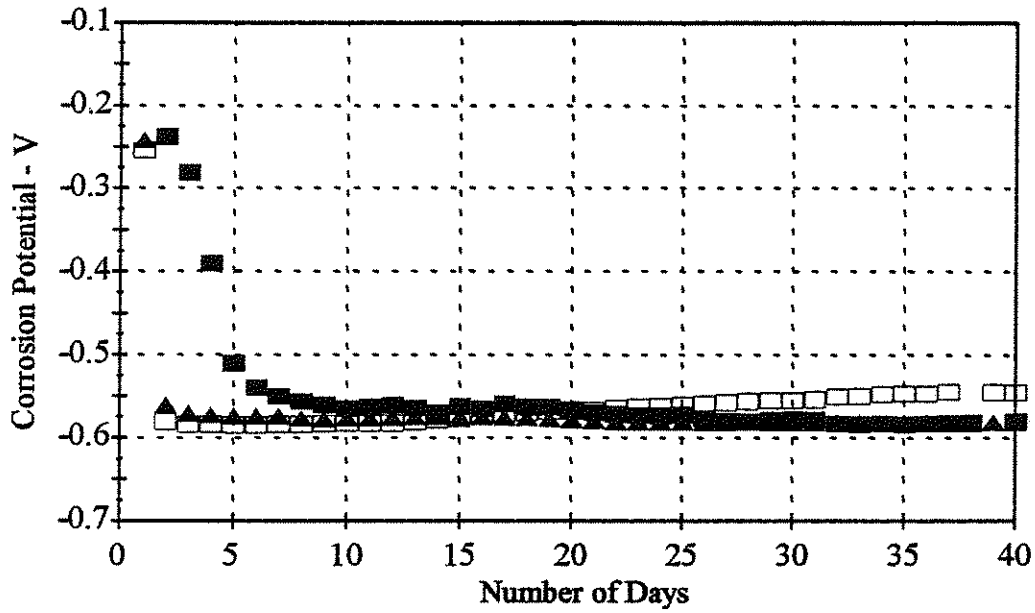


Fig. 5 Corrosion potential versus time for potential test specimens with hot-rolled regular steel, H, subjected to a 6.04 m ion (15%) solution of NaCl

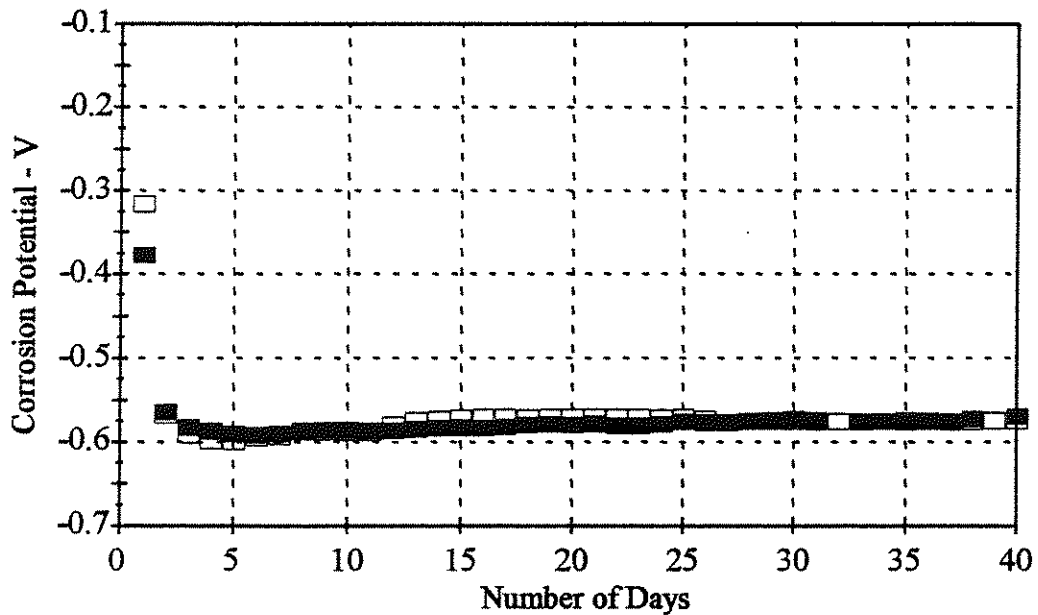


Fig. 6 Corrosion potential versus time for potential test specimens with Thermex treated regular steel, T, subjected to a 6.04 m ion (15%) solution of NaCl

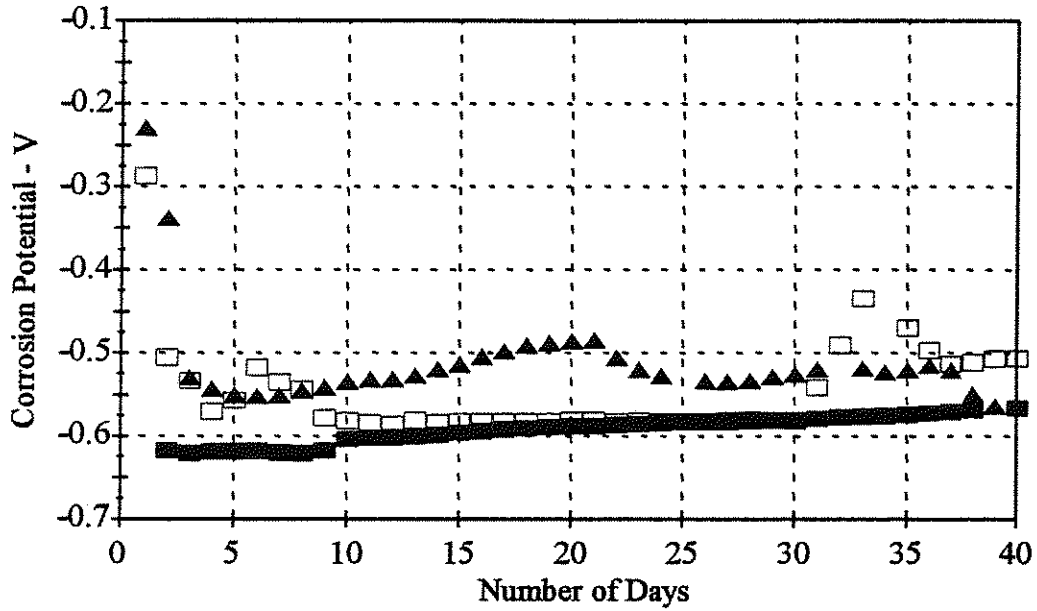


Fig. 7 Corrosion potential versus time for potential test specimens with hot-rolled corrosion resistant steel, CRSH, subjected to a 6.04 m ion (15%) solution of NaCl

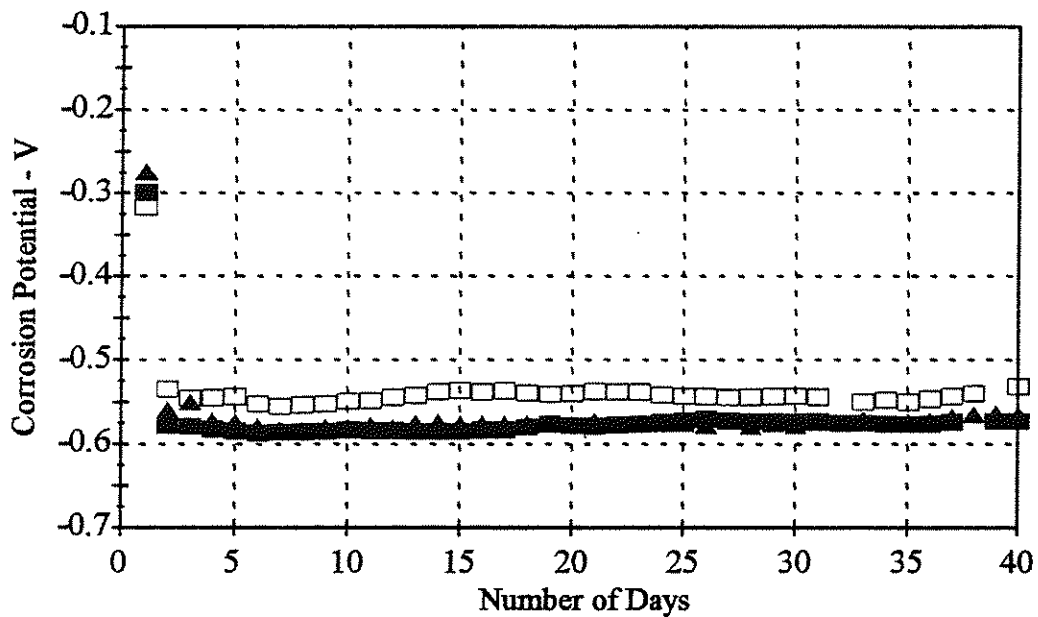


Fig. 8 Corrosion potential versus time for potential test specimens with Thermex treated corrosion resistant steel, CRST, subjected to a 6.04 m ion (15%) solution of NaCl

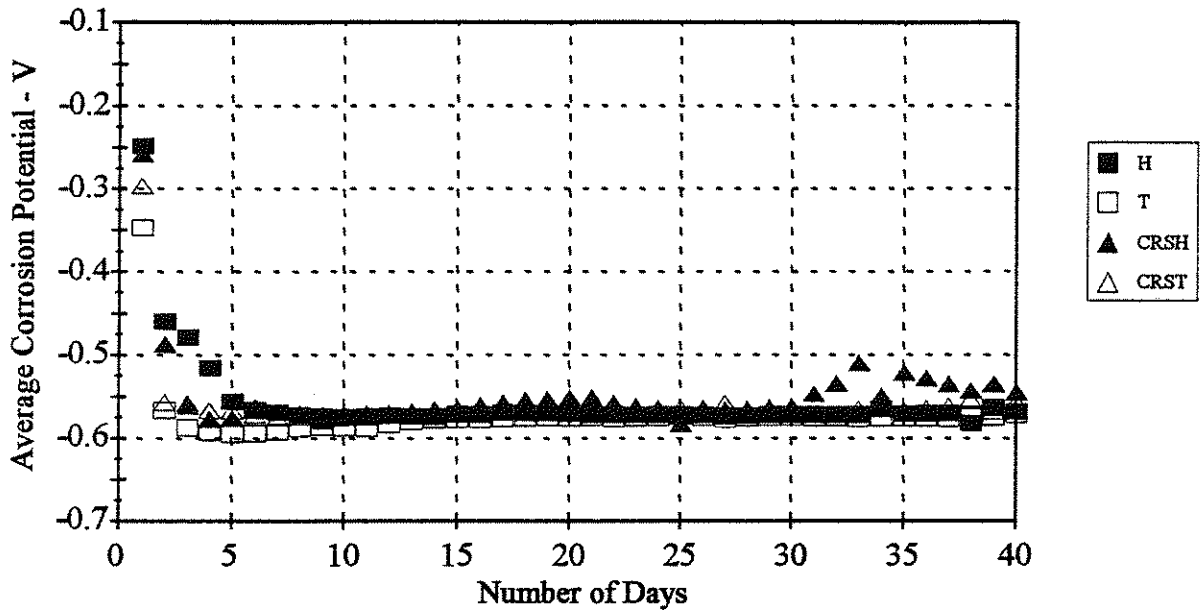


Fig. 9 Average corrosion potential versus time for potential test specimens with hot-rolled and Thermex treated regular steels, H and T, and hot-rolled and Thermex treated corrosion resistant steels, CRSH and CRST, subjected to a 6.04 m ion (15%) solution of NaCl

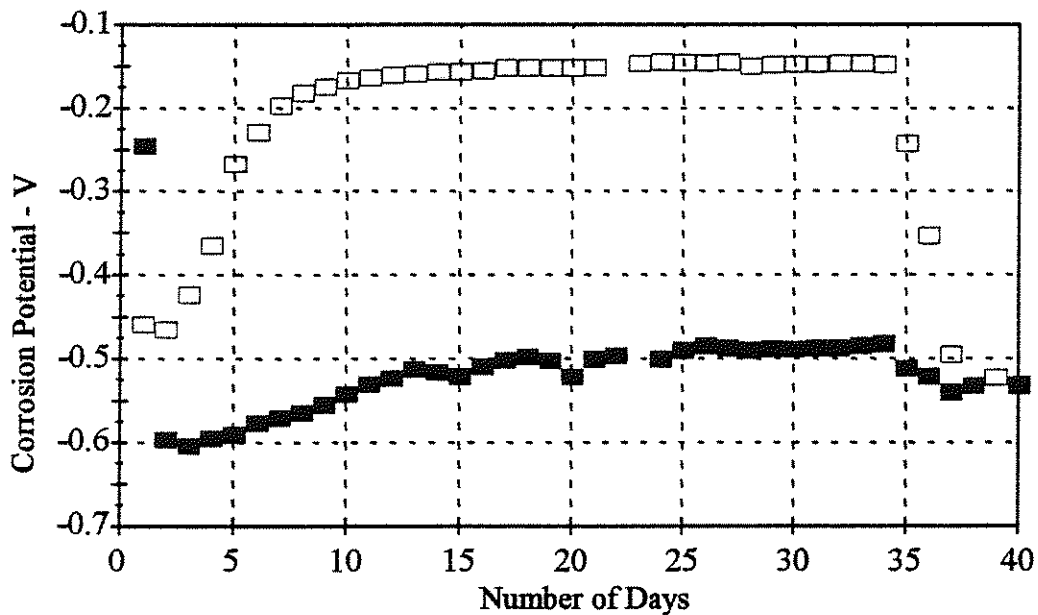


Fig. 10 Corrosion potential versus time for potential test specimens with hot-rolled regular steel, H, subjected to a 6.04 m ion (15%) concentration of NaCl in a simulated pore solution

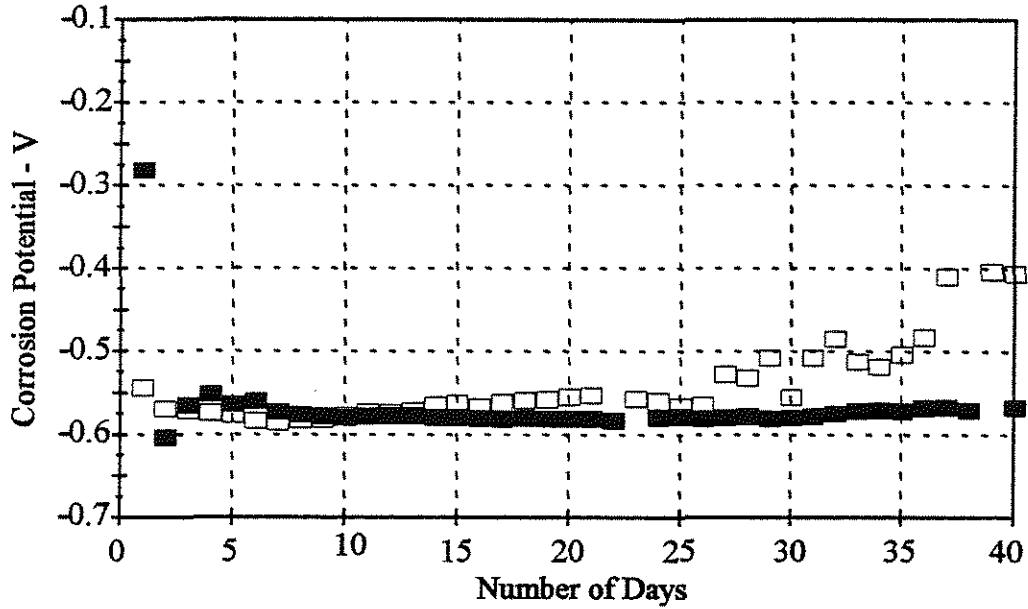


Fig. 11 Corrosion potential versus time for potential test specimens with Thermex treated corrosion resistant steel, CRST, subjected to a 6.04 m ion (15%) concentration of NaCl in a simulated pore solution

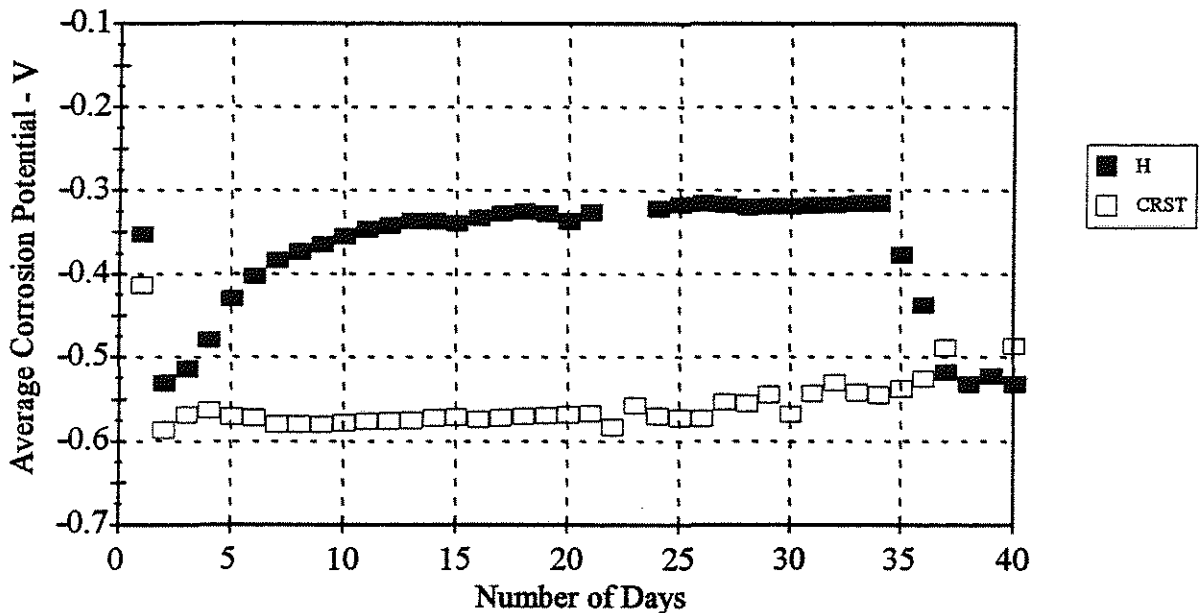


Fig. 12 Average corrosion potential versus time for potential test specimens with hot-rolled regular steel, H, and Thermex treated corrosion resistant steel, CRST, subjected to a 6.04 m ion (15%) concentration of NaCl in a simulated pore solution

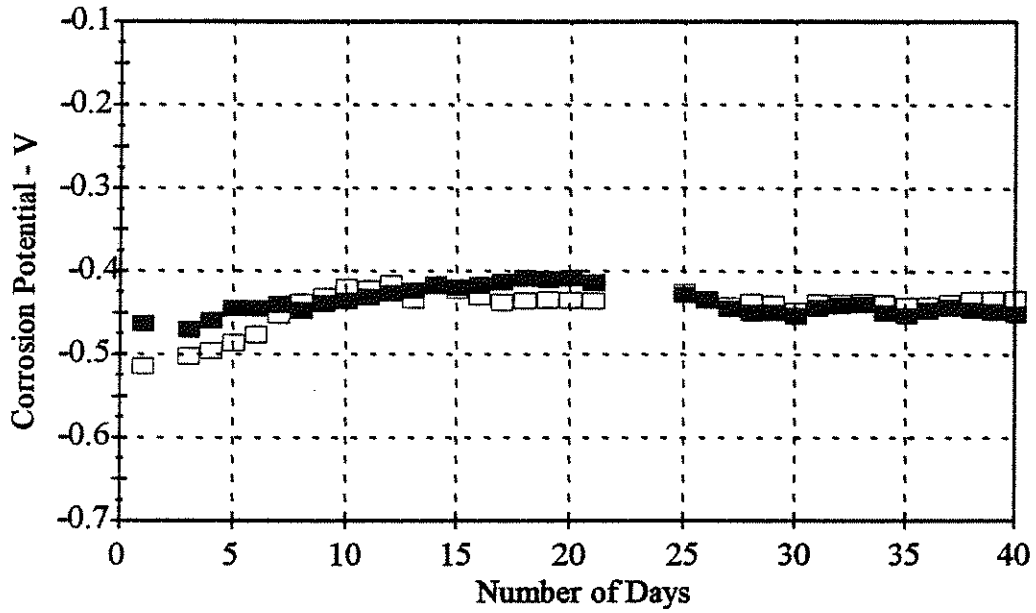


Fig. 13 Corrosion potential versus time for potential test specimens with Thermex treated regular steel, T, subjected to a simulated pore solution

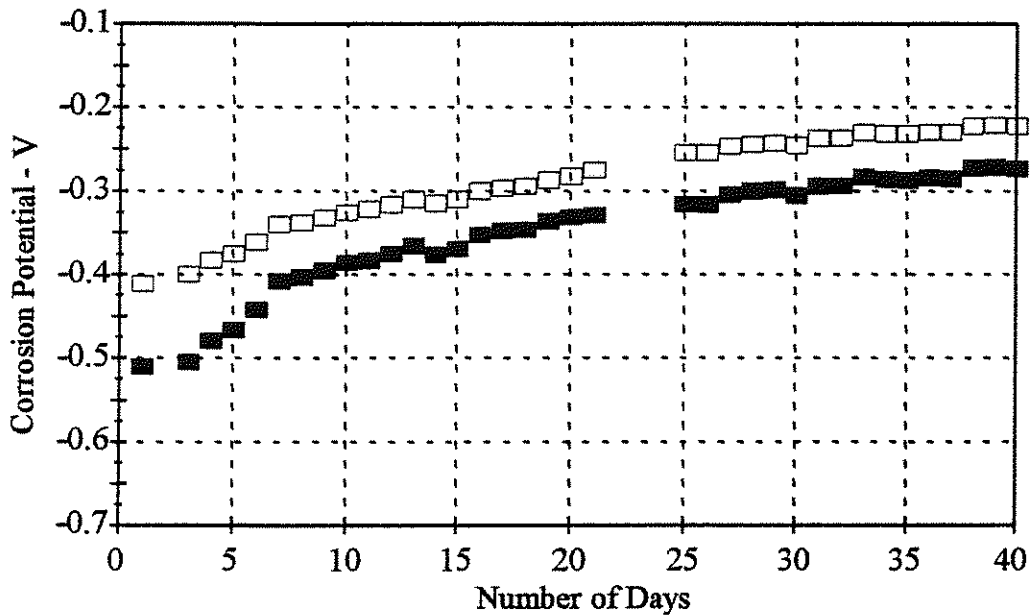


Fig. 14 Corrosion potential versus time for potential test specimens with hot-rolled corrosion resistant steel, CRSH, subjected to a simulated pore solution

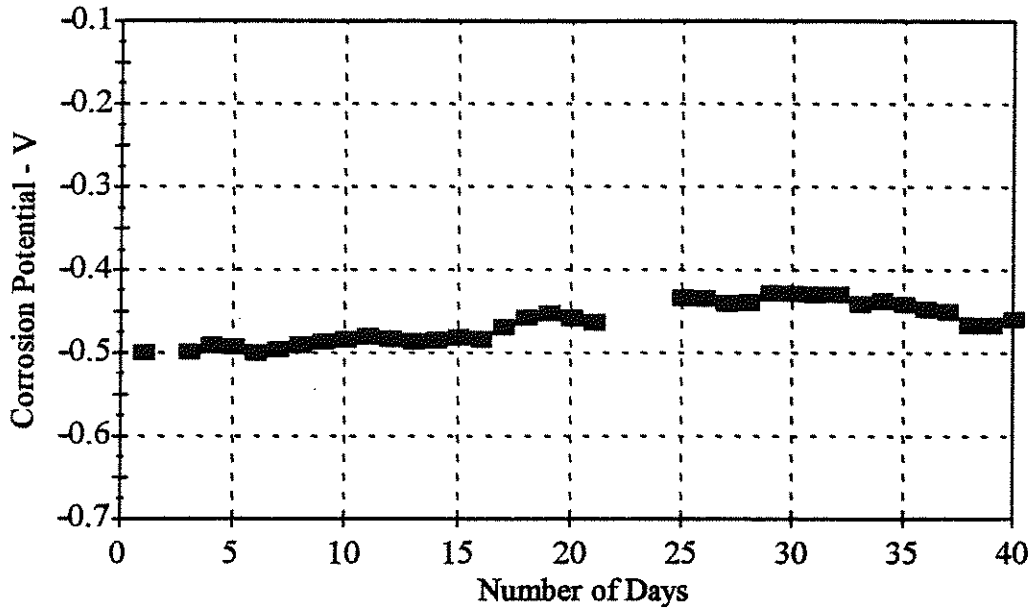


Fig. 15 Corrosion potential versus time for potential test specimens with Thermex treated corrosion resistant steel, CRST, subjected to a simulated pore solution

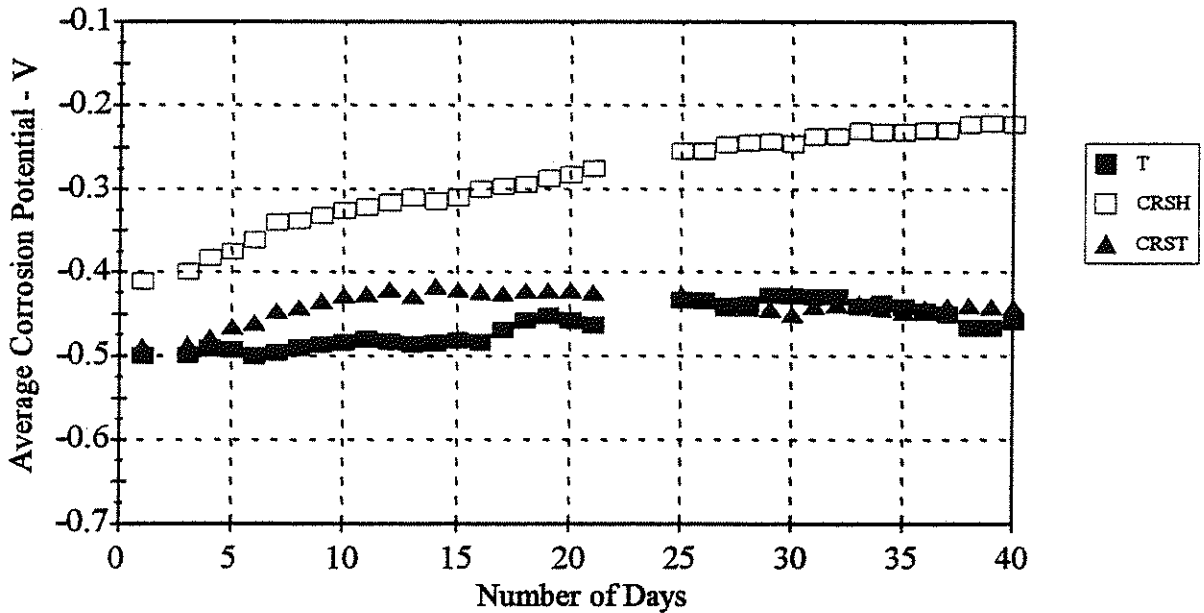


Fig. 16 Average corrosion potential versus time for potential test specimens with Thermex treated regular steel, T, and hot-rolled and Thermex treated corrosion resistant steels, CRSH and CRST, subjected to a simulated pore solution

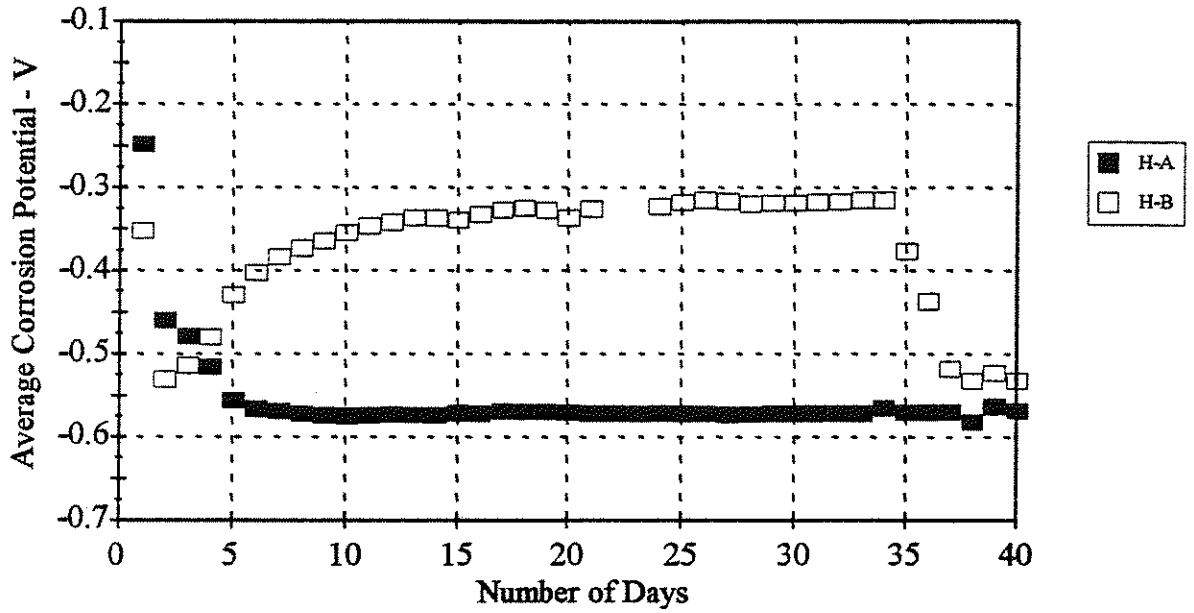


Fig. 17 Average corrosion potential versus time for potential test specimens with hot-rolled regular steel, H, subjected to (A) a 6.04 m ion (15%) solution of NaCl and (B) a 6.04 m ion (15%) concentration of NaCl in a simulated pore solution

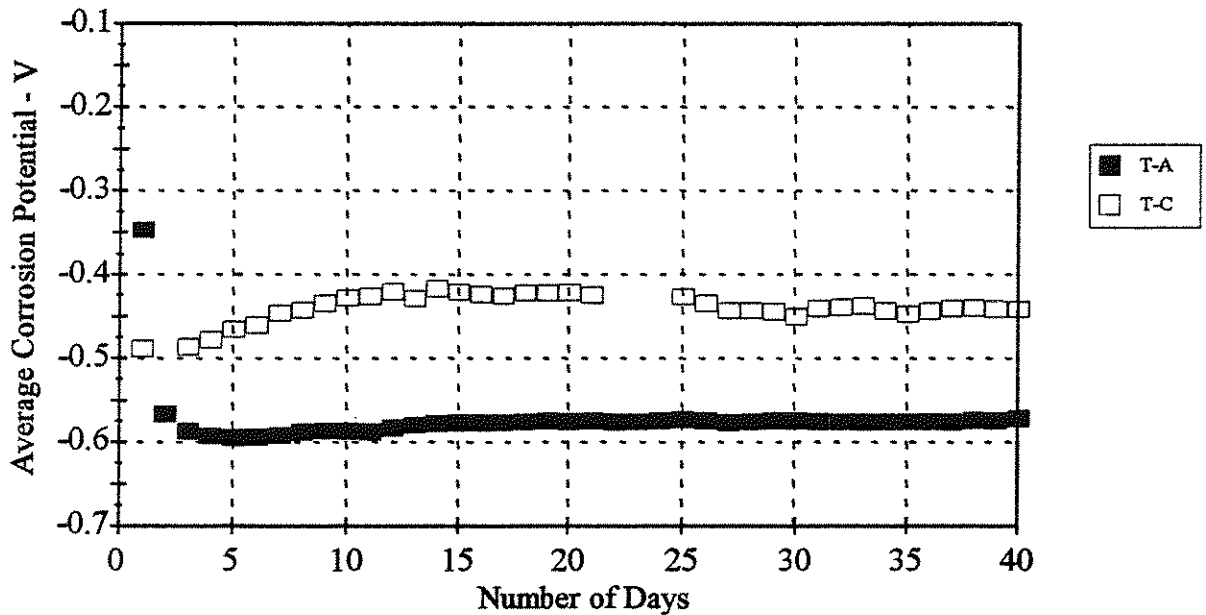


Fig. 18 Average corrosion potential versus time for potential test specimens with Thermex treated regular steel, T, subjected to (A) a 6.04 m ion (15%) solution of NaCl and (C) a simulated pore solution

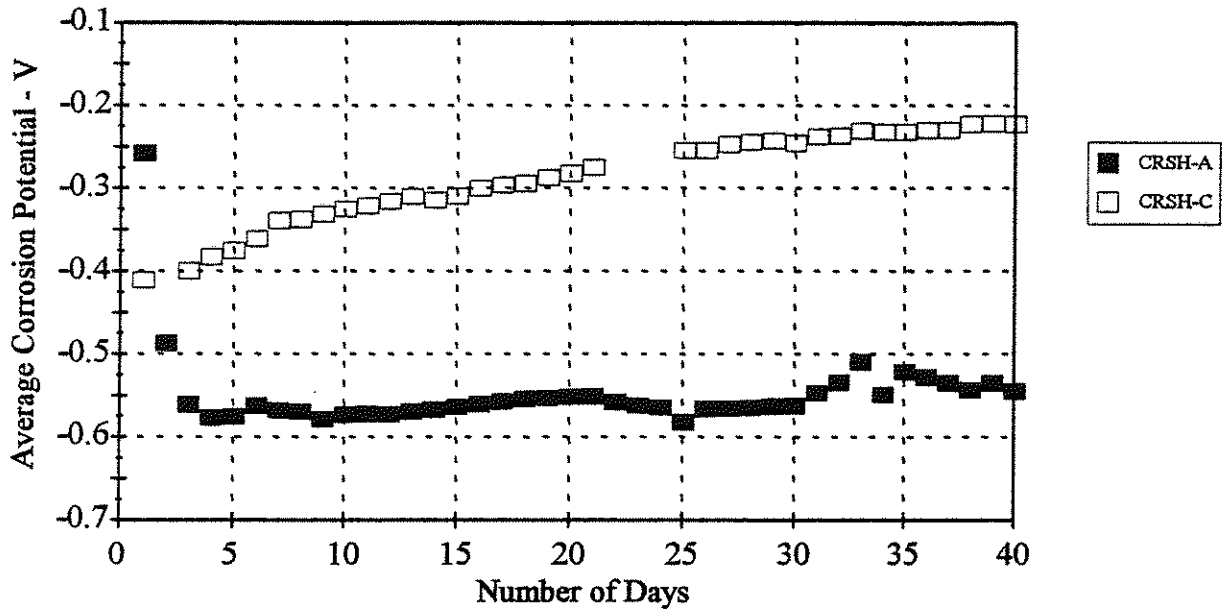


Fig. 19 Average corrosion potential versus time for potential test specimens with hot-rolled corrosion resistant steel, CRSH, subjected to (A) a 6.04 m ion (15%) solution of NaCl and (C) a simulated pore solution

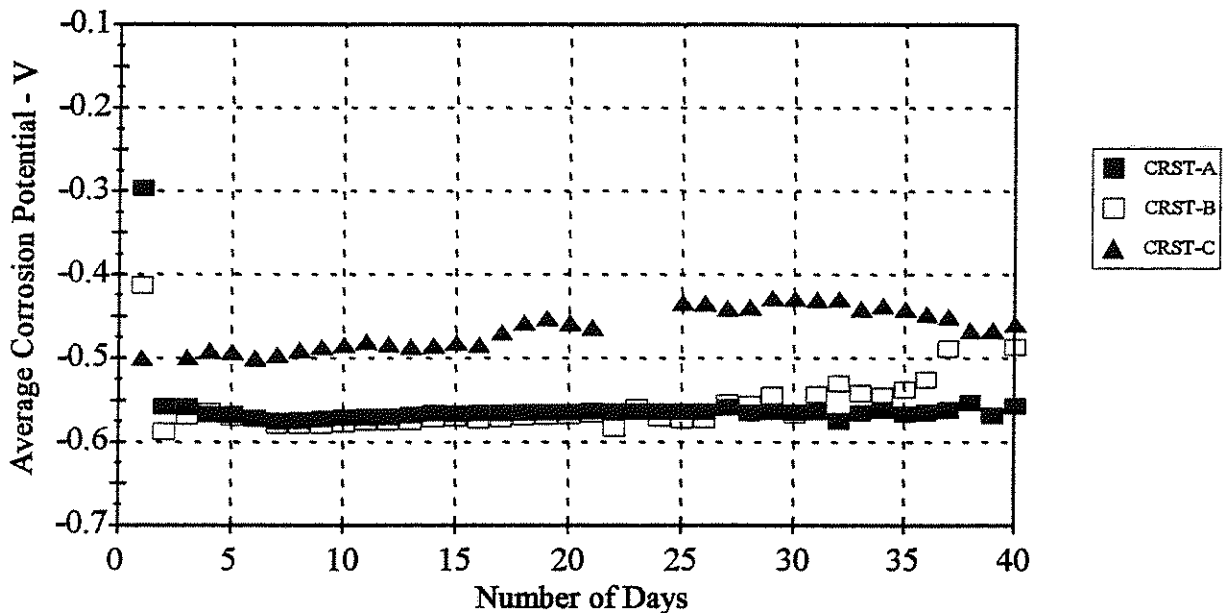


Fig. 20 Average corrosion potential versus time for potential test specimens with Thermex treated corrosion resistant steel, CRST, subjected to (A) a 6.04 m ion (15%) solution of NaCl, (B) a 6.04 m ion (15%) concentration of NaCl in a simulated pore solution, and (C) a simulated pore solution

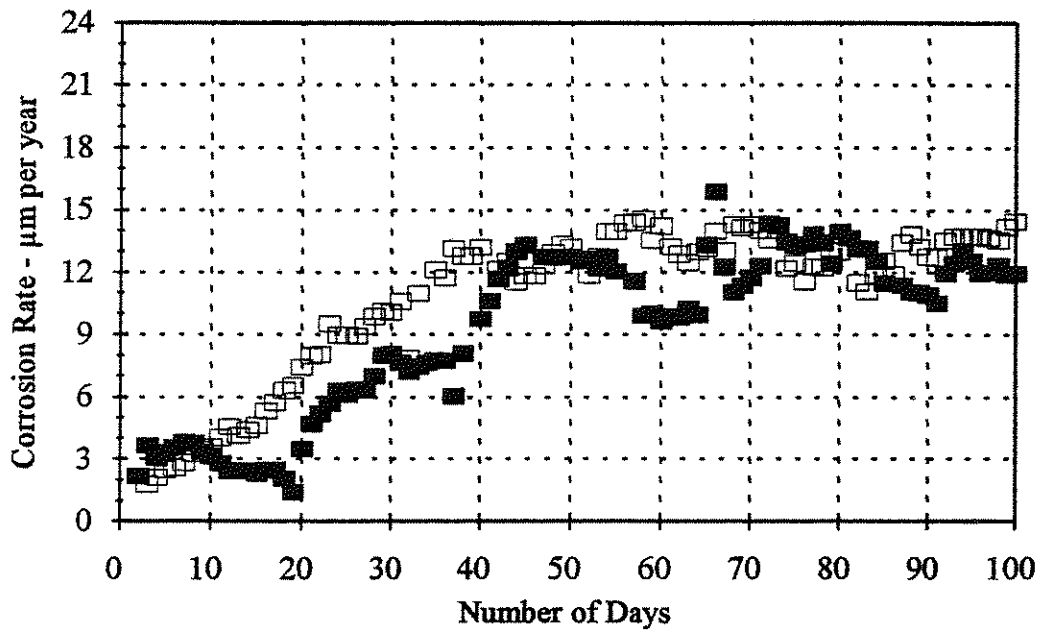


Fig. 21 Corrosion rate versus time for macrocell test specimens with hot-rolled regular steel, H, subjected to a simulated pore solution deficient in NaOH, cathode, and a 6.04 m ion (15%) solution of NaCl, anode ($25.4 \mu\text{m per year} = 1 \text{ mil per year} = 0.001 \text{ in. per year}$)

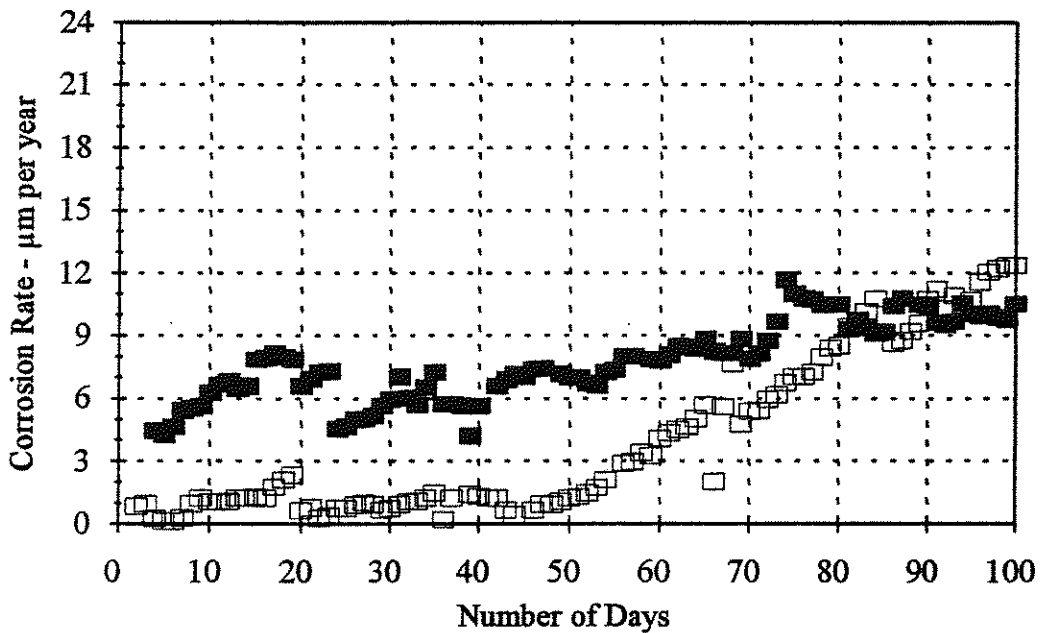


Fig. 22 Corrosion rate versus time for macrocell test specimens with Thermex treated regular steel, T, subjected to a simulated pore solution deficient in NaOH, cathode, and a 6.04 m ion (15%) solution of NaCl, anode ($25.4 \mu\text{m per year} = 1 \text{ mil per year} = 0.001 \text{ in. per year}$)

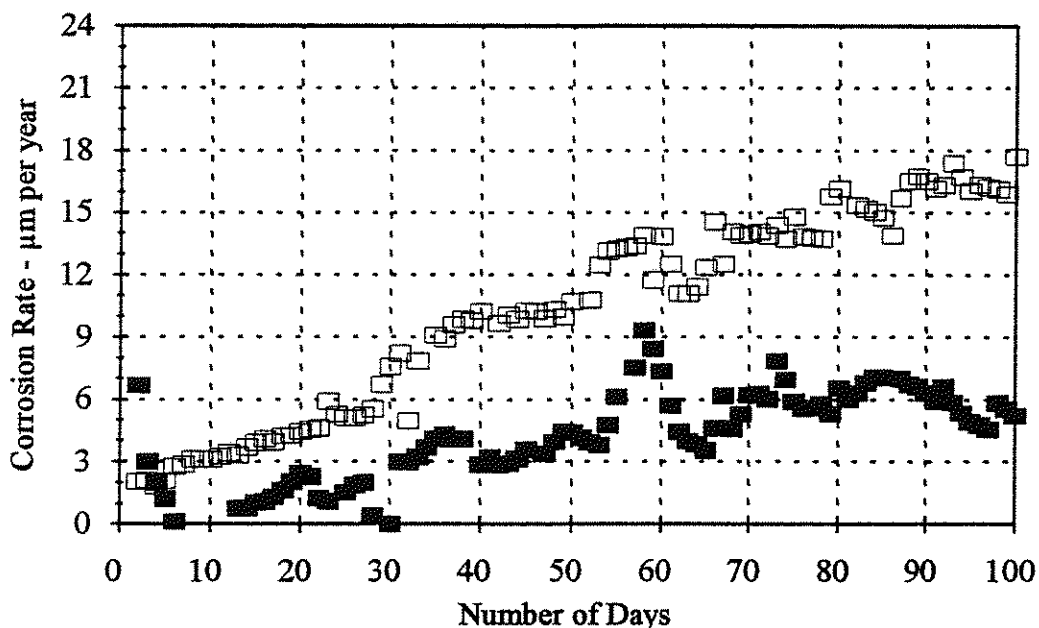


Fig. 23 Corrosion rate versus time for macrocell test specimens with hot-rolled corrosion resistant steel, CRSH, subjected to a simulated pore solution deficient in NaOH, cathode, and a 6.04 m ion (15%) solution of NaCl, anode (25.4 μm per year = 1 mil per year = 0.001 in. per year)

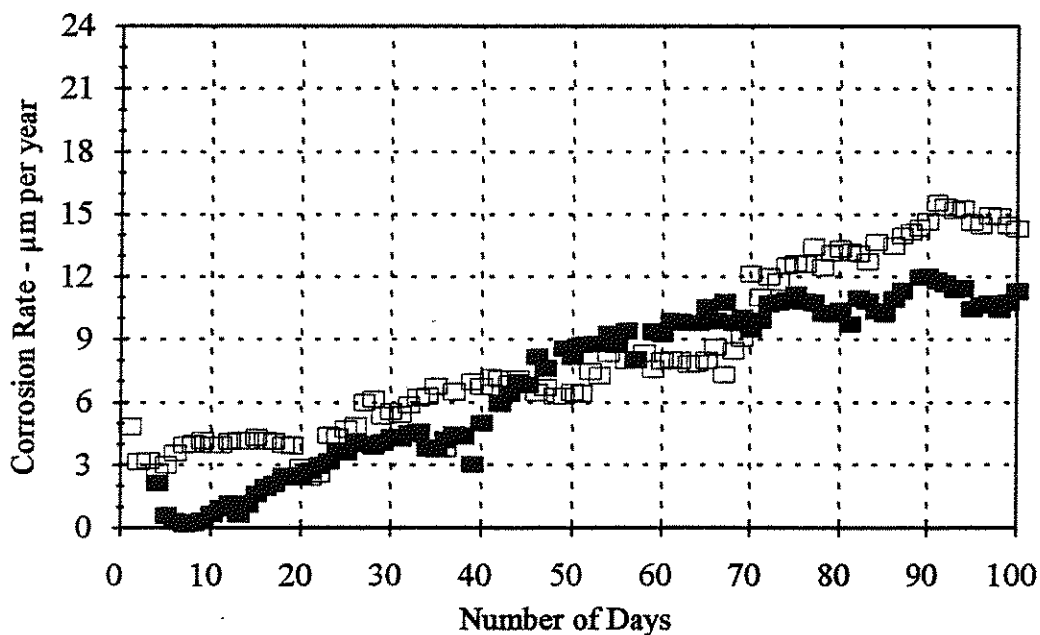


Fig. 24 Corrosion rate versus time for macrocell test specimens with Thermex treated corrosion resistant steel, CRST, subjected to a simulated pore solution deficient in NaOH, cathode, and a 6.04 m ion (15%) solution of NaCl, anode (25.4 μm per year = 1 mil per year = 0.001 in. per year)

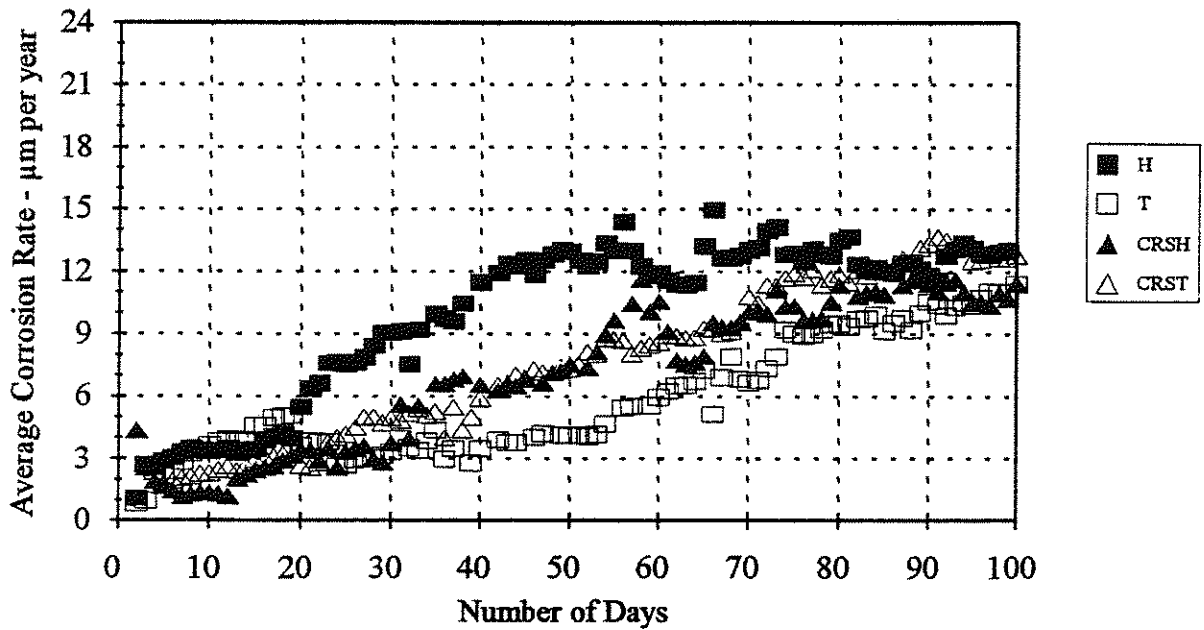


Fig. 25 Average corrosion rate versus time for macrocell test specimens with hot-rolled and Thermex treated regular steels, H and T, and hot-rolled and Thermex treated corrosion resistant steels, CRSH and CRST, subjected to simulated pore solution deficient in NaOH, cathode, and a 6.04 m ion (15%) solution of NaCl, anode (25.4 μm per year = 1 mil per year = 0.001 in. per year)

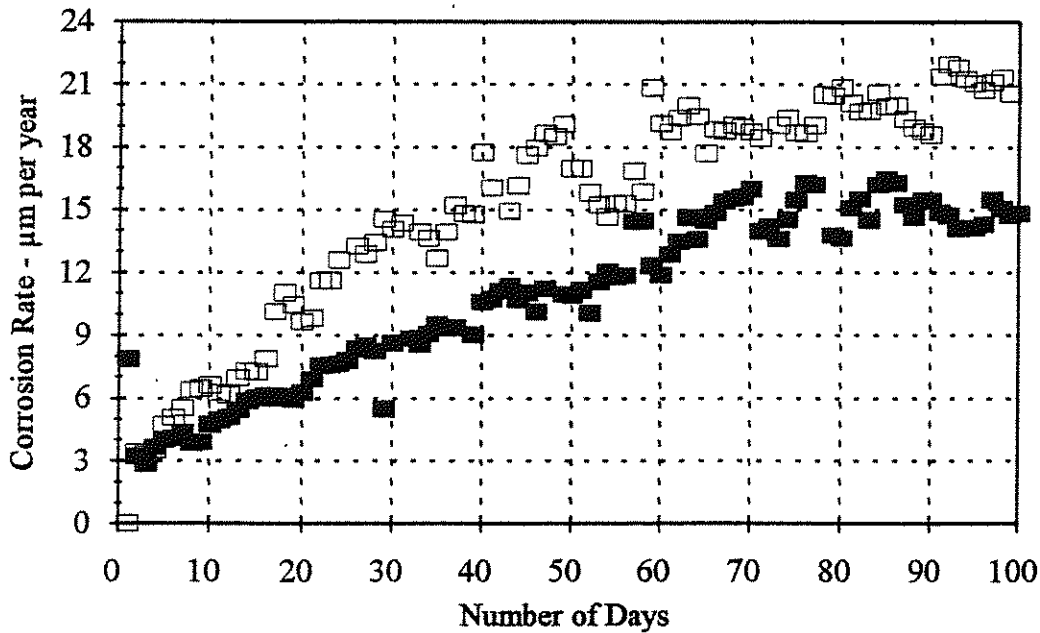


Fig. 26 Corrosion rate versus time for macrocell test specimens with hot-rolled regular steel, H, subjected to a simulated pore solution, cathode, and a 6.04 m ion (15%) solution of NaCl, anode (25.4 μm per year = 1 mil per year = 0.001 in. per year)

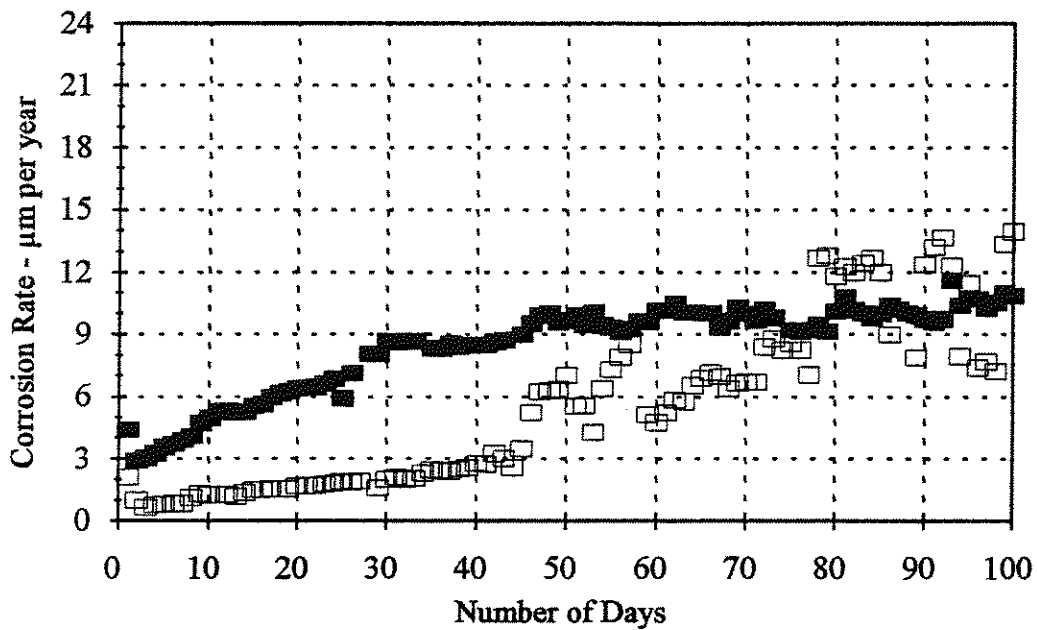


Fig. 27 Corrosion rate versus time for macrocell test specimens with Thermex treated regular steel, T, subjected to a simulated pore solution, cathode, and a 6.04 m ion (15%) solution of NaCl, anode (25.4 μm per year = 1 mil per year = 0.001 in. per year)

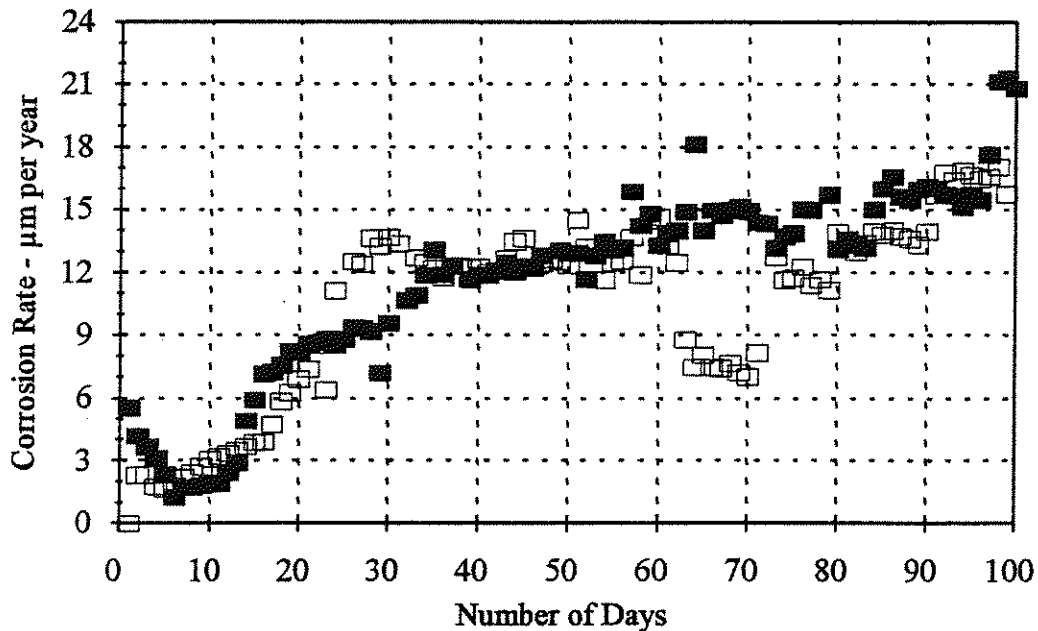


Fig. 28 Corrosion rate versus time for macrocell test specimens with hot-rolled corrosion resistant steel, CRSH, subjected to a simulated pore solution, cathode, and a 6.04 m ion (15%) solution of NaCl, anode (25.4 μm per year = 1 mil per year = 0.001 in. per year)

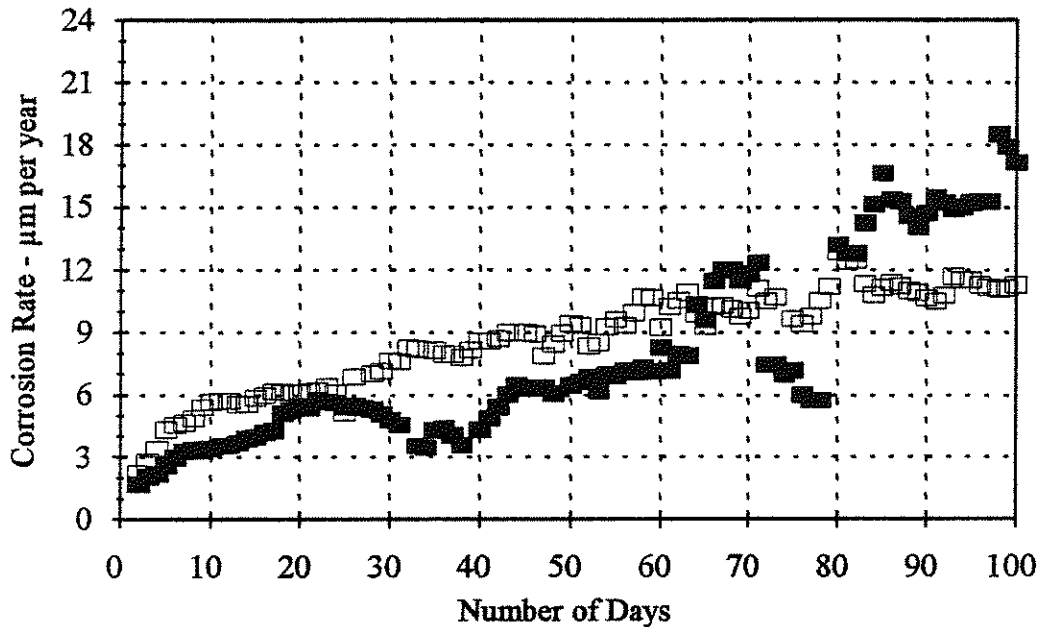


Fig. 29 Corrosion rate for macrocell test specimens with Thermex treated corrosion resistant steel, CRST, subjected to a simulated pore solution, cathode, and a 6.04 m ion (15%) solution of NaCl, anode (25.4 μm per year = 1 mil per year = 0.001 in. per year)

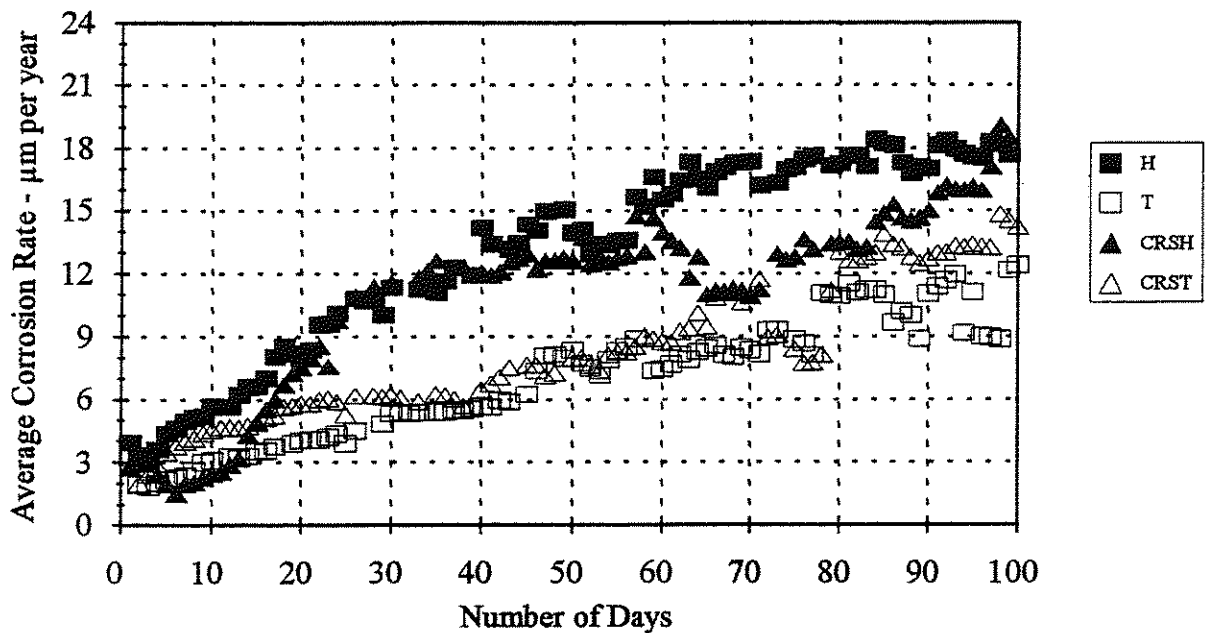


Fig. 30 Average corrosion rate versus time for macrocell test specimens with hot-rolled and Thermex treated regular steels, H and T, and hot-rolled and Thermex treated corrosion resistant steels, CRSH and CRST, subjected to a simulated pore solution, cathode, and a 6.04 m ion (15%) solution of NaCl, anode (25.4 μm per year = 1 mil per year = 0.001 in. per year)

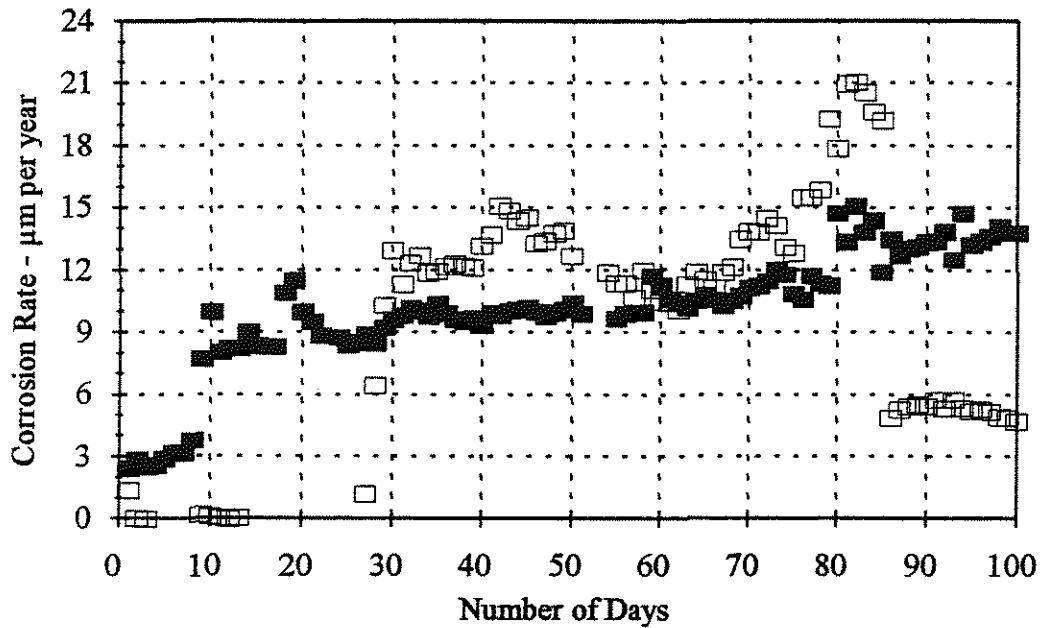


Fig. 31 Corrosion rate versus time for macrocell test specimens with hot-rolled regular steel, H, subjected to a simulated pore solution, cathode, and a 6.04 m ion (15%) concentration of NaCl in a simulated pore solution, anode (25.4 μm per year = 1 mil per year = 0.001 in. per year)

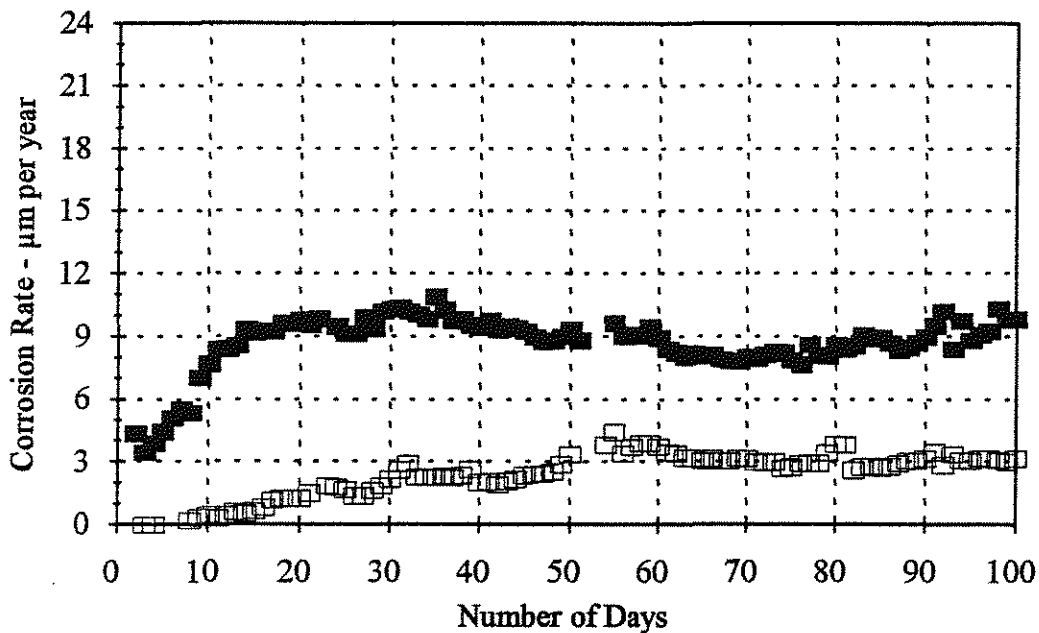


Fig. 32 Corrosion rate versus time for macrocell test specimens with Thermex treated corrosion resistant steel, CRST, subjected to a simulated pore solution, cathode, and a 6.04 m ion (15%) concentration of NaCl in a simulated pore solution, anode (25.4 μm per year = 1 mil per year = 0.001 in. per year)

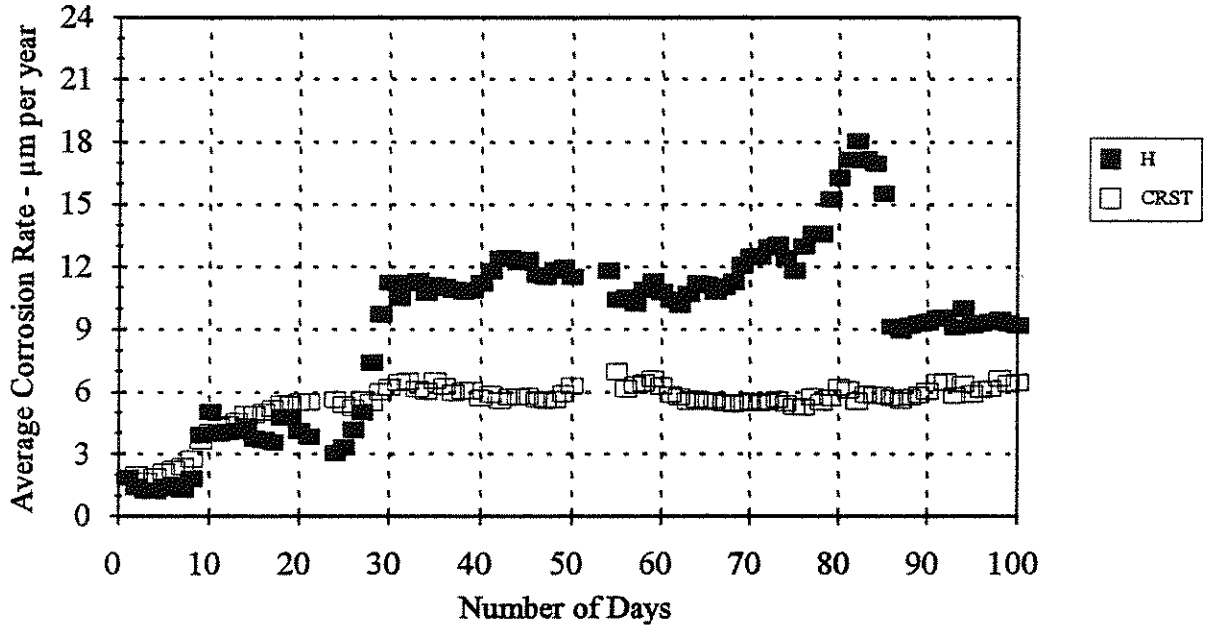


Fig. 33 Average corrosion rate versus time for macrocell test specimens with hot-rolled regular steel, H, and Thermex treated corrosion resistant steel, CRST, subjected to a simulated pore solution, cathode, and a 6.04 m ion (15%) concentration of NaCl in a simulated pore solution, anode ($25.4 \mu\text{m per year} = 1 \text{ mil per year} = 0.001 \text{ in. per year}$)

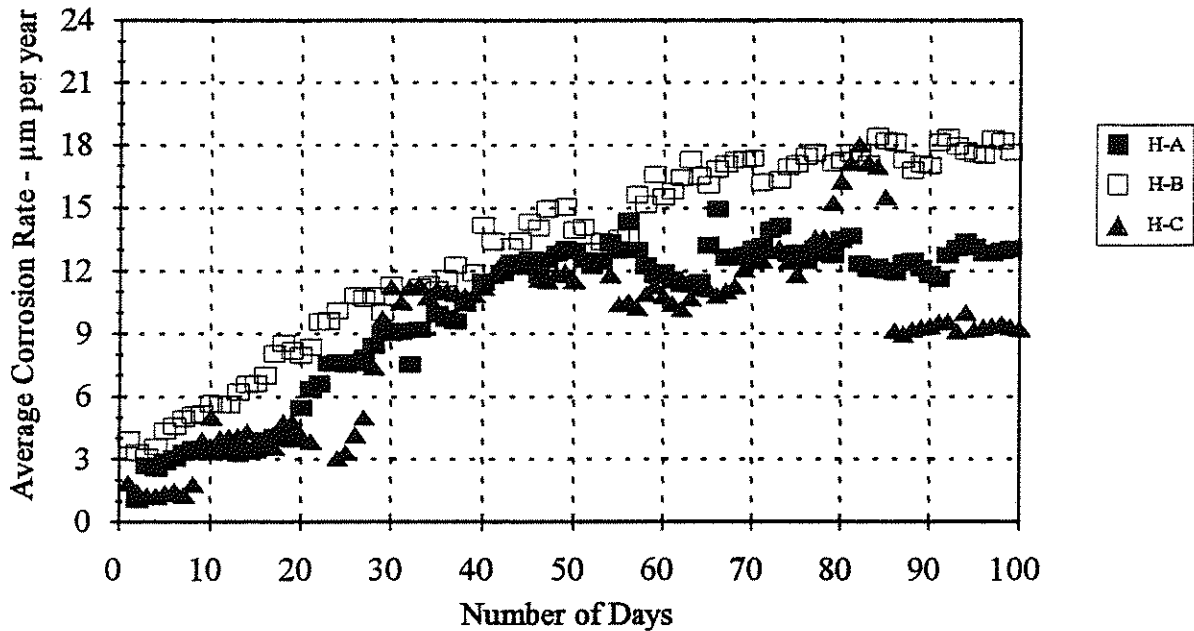


Fig. 34 Average corrosion rate versus time for macrocell test specimens with hot-rolled regular steel, H, subjected to (A) a simulated pore solution deficient in NaOH, cathode, and a 6.04 m ion (15%) solution of NaCl, anode, (B) a simulated pore solution, cathode, and a 6.04 m ion (15%) solution of NaCl, anode, and (C) a simulated pore solution, cathode, and a 6.04 m ion (15%) concentration of NaCl in a simulated pore solution, anode ($25.4 \mu\text{m per year} = 1 \text{ mil per year} = 0.001 \text{ in. per year}$)

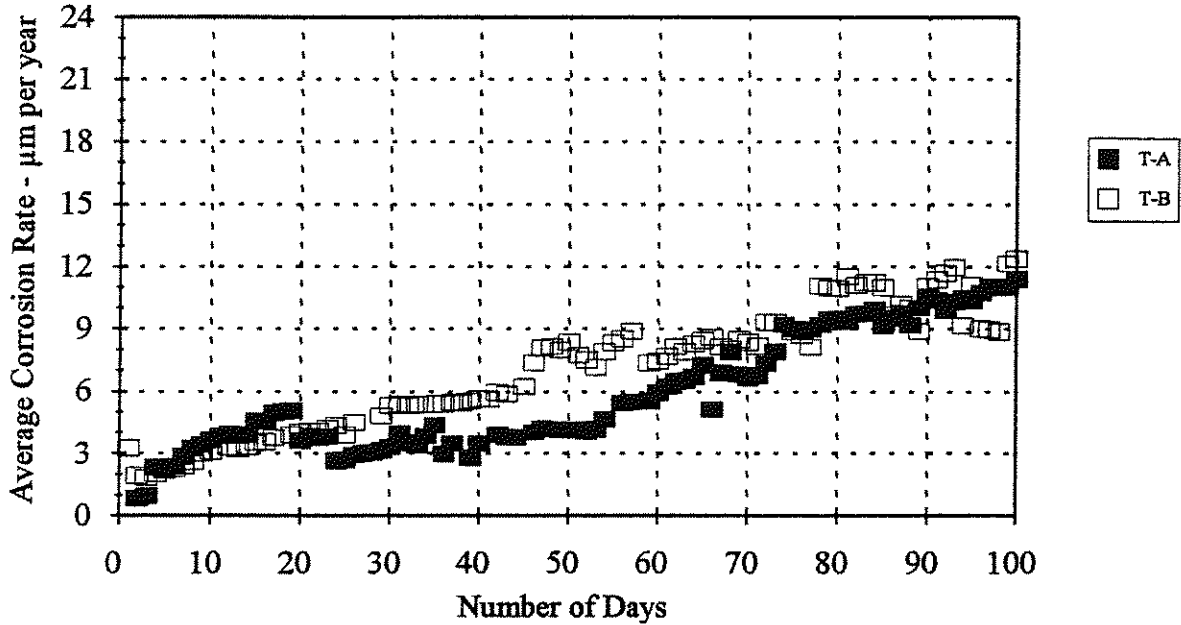


Fig. 35 Average corrosion rate versus time for macrocell test specimens with Thermex treated regular steel, T, subjected to (A) a simulated pore solution deficient in NaOH, cathode, and a 6.04 m ion (15%) solution of NaCl, anode, and (B) a simulated pore solution, cathode, and a 6.04 m ion (15%) solution of NaCl, anode ($25.4 \mu\text{m per year} = 1 \text{ mil per year} = 0.001 \text{ in. per year}$)

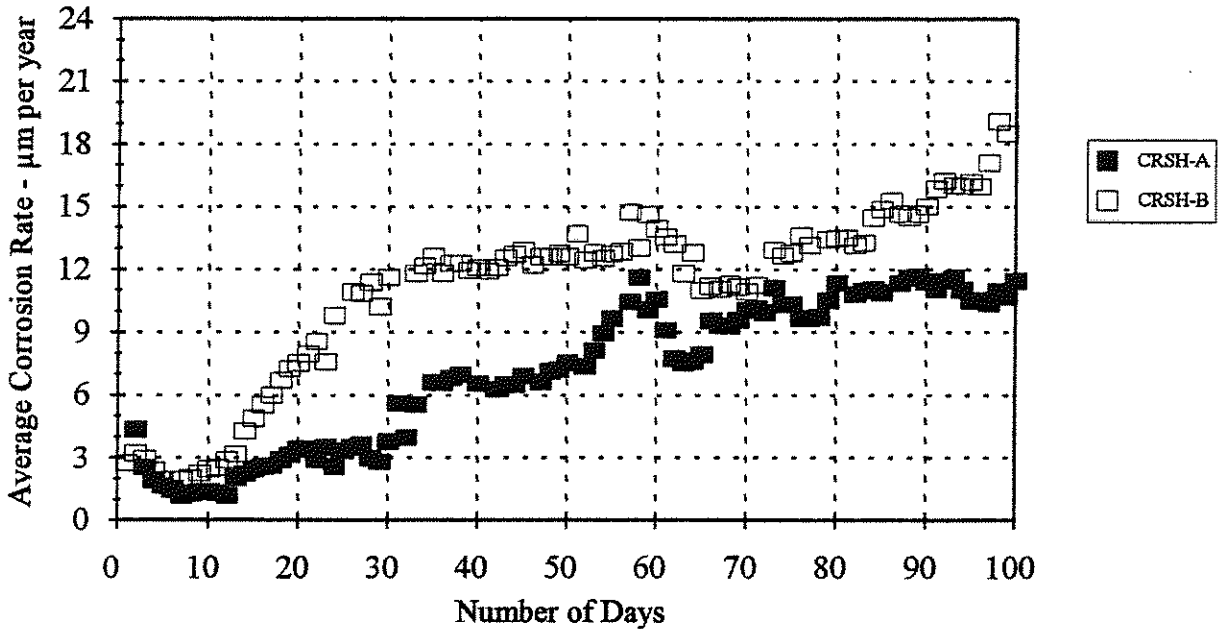


Fig. 36 Average corrosion rate versus time for macrocell test specimens with hot-rolled corrosion resistant steel, CRSH, subjected to (A) a simulated pore solution deficient in NaOH, cathode, and a 6.04 m ion (15%) solution of NaCl, anode, and (B) a simulated pore solution, cathode, and a 6.04 m ion (15%) solution of NaCl, anode ($25.4 \mu\text{m per year} = 1 \text{ mil per year} = 0.001 \text{ in. per year}$)

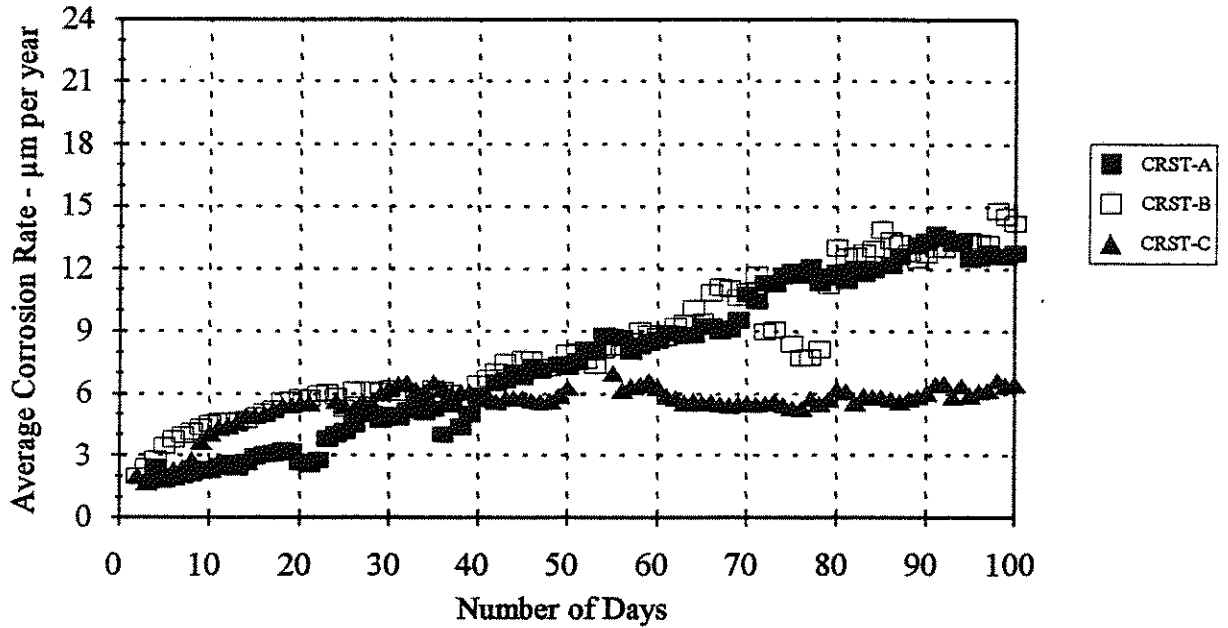


Fig. 37 Average corrosion rate versus time for macrocell test specimens with Thermex treated corrosion resistant steel, CRST, subjected to (A) a simulated pore solution deficient in NaOH, cathode, and a 6.04 m ion (15%) solution of NaCl, anode, (B) a simulated pore solution, cathode, and a 6.04 m ion (15%) solution of NaCl, anode, and (C) a simulated pore solution, cathode, and a 6.04 m ion (15%) concentration of NaCl in a simulated pore solution, anode (25.4 μm per year = 1 mil per year = 0.001 in. per year)