# CORROSION-RESISTANT REINFORCING STEELS

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## ABSTRACT

Research to evaluate the corrosion performance of duplex, stainless steel-clad, microalloyed, and MMFX Microcomposite reinforcing steels for use in reinforced concrete bridge decks is reported. The steels are compared with uncoated conventional steel in terms of corrosion rate and with uncoated and epoxy-coated steel in terms of life expectancy and cost effectiveness in reinforced concrete bridge decks. The duplex and stainless steel-clad bars corrode at a rate equal to 1/50 to 1/250 of the rate of conventional steel and are viable replacements for epoxy-coated steel. MMFX steel corrodes at 1/3 to 2/3 of the rate of conventional reinforcement, performance that is not adequate to justify its use without a supplementary corrosion protection system. The microalloyed steels corrode at about 90% of the rate of conventional reinforcement and are not recommended for use in reinforced concrete bridge decks.

**Key words:** Bridge decks, Costs, Corrosion, Design life, Reinforcing steel

## INTRODUCTION

Corrosion has a major impact on both the nation's economy and infrastructure[1]. Corrosion in bridges, and especially the corrosion of reinforcing steel in reinforced concrete bridge decks, is a major contributor to maintenance costs and the need for bridge rehabilitation[2].

Since the late 1960s, many methods have been developed to limit or prevent the corrosion of reinforcing steel. These methods can be placed in four categories: (1) alternate reinforcement and slab design, (2) barrier methods, (3) electro-chemical methods, and (4) corrosion inhibitors. Researchers at the University of Kansas are currently involved in a long-term program to evaluate and improve corrosion protection systems for reinforced concrete bridges, with efforts that address the first, second, and fourth categories. This paper deals with a portion of that research and describes the latest efforts to evaluate corrosion-resistant reinforcing steels.

## RESEARCH PROGRAM

The current study addresses conventional reinforcing steels (designated N1, N2, and N3 in the study), microalloyed steel (similar to conventional steel, but with increased fractions of chromium, copper, and phosphorous – all less than 1%) (CRPT1, CRPT2, and CRT), epoxy-coated steel, MMFX microcomposite, a prototype 304 stainless steel-clad, and duplex stainless reinforcing steels (2101, pickled 2101, 2205, and pickled 2205).

The research program includes laboratory studies, field test specimens, the construction of five bridges with selected corrosion-protection systems, and monitoring both new and existing bridges. Corrosion-protection systems are compared based on life expectancy and cost. The balance of this paper will describe the laboratory tests and the initial estimates of life expectancy and cost effectiveness of the reinforcing steels in the program.

### LABORATORY TESTS

Results for three laboratory tests, the rapid macrocell test, the Southern Exposure test, and cracked beam test, are presented in this paper.

#### Macrocell Test

The *macrocell test*, shown in Fig. 1, involves placing one specimen (with or without a mortar coating) in a plastic container filled with simulated pore solution combined with NaCl[4]. The specimen serves as the anode. The results shown in this paper are based on a 1.6 molal ion concentration of NaCl, the solution used for the majority of the tests. Two other specimens, which serve as the cathode, are placed in a second container with simulated pore solution. A mortar fill, with the same composition used for the mortar-clad (mortar-wrapped) specimens, is used as an additional buffering medium for specimens with a mortar coating. The mortar represents the mortar constituent of concrete, with a water-cement ratio of 0.5 and a sandcement ratio of 2. The solutions in the two containers are connected by a salt bridge and the reinforcing steel at the anode is electrically connected across a 10-ohm resistor to the two bars serving as the cathode. Air, scrubbed to remove $CO_2$, is pumped into the solution at the cathode. The solutions are changed after the fifth and tenth weeks to further limit the effects of carbonation during this 15-week test. Once a day for the first week and then weekly thereafter, the voltage drop is measured across the 10-ohm resistor to determine the corrosion current, which can then be converted to a corrosion rate using Faraday's Law[5]. Following the corrosion rate readings, the circuit is broken for two hours and the corrosion potential of the anode and cathode, with respect to a saturated calomel electrode (CSE), is measured. If needed, the test is extended beyond 15 weeks.

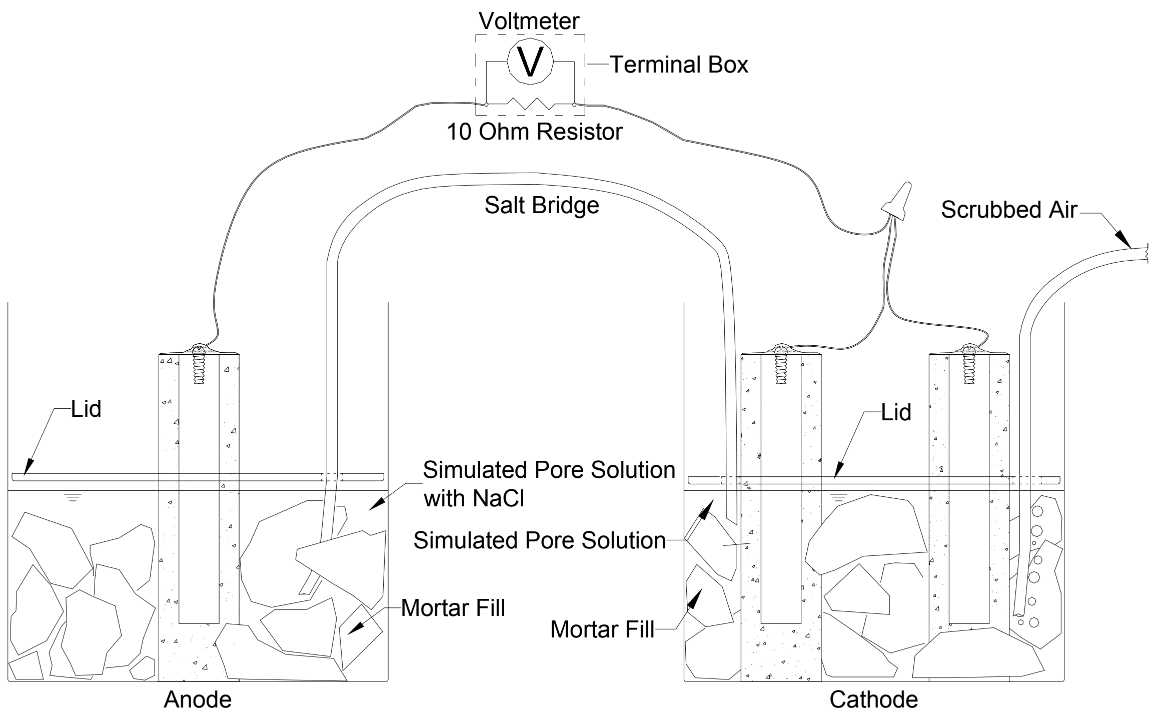



Fig. 1 Schematic of Macrocell Test[4]

Southern Exposure Test

The *Southern Exposure* test specimen, shown in Fig. 2, consists of a small concrete slab, 12 in. square by 7 in. deep with an integrally cast concrete dam to allow ponding of a 15% NaCl solution. The slab contains two top and four bottom reinforcing bars. Each mat has a 1 in. cover. The top bars are connected to the bottom bars across a 10-ohm resistor. The slab is ponded with the salt solution for four days. The solution is then removed, and the slab is dried at 100°F for three days. The cycle is repeated for 12 weeks, after which the slab is ponded continually for 12 weeks. The 24-week cycle is repeated three more times, for a total test period of 96 weeks. Once a week, the corrosion rate and corrosion potential of the bars is measured. The corrosion potential is measured with respect to a copper-copper sulfate electrode (CSE). The mat-to-mat resistance is also measured.

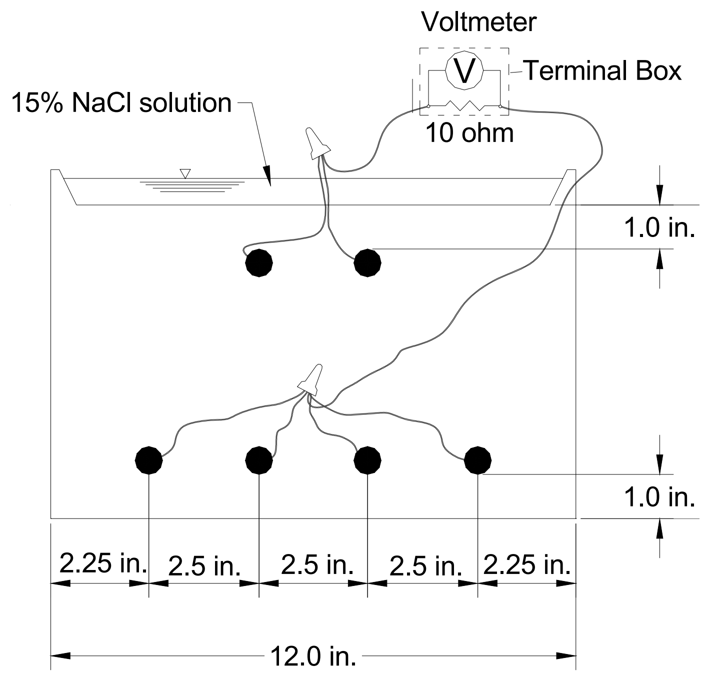



Fig. 2 Test Specimen for Southern Exposure Test[4]

Cracked Beam Test

The *cracked beam* test specimen, shown in Fig. 3, is half the size of the Southern Exposure specimen and contains one bar in the top mat and two bars in the bottom mat. When the concrete is cast, a 0.3-mm (0.012 in.) thick stainless steel shim over and parallel to the top reinforcing bar is placed in the fresh concrete to simulate a settlement crack to the surface of the bar. The shim is removed within 24 hours of concrete placement. The exposure conditions and measurements used for the cracked beam test are the same as those used for the Southern Exposure test.

LIFE EXPECTANCY AND COST EFFECTIVENESS

Life expectancy is estimated using a combination of laboratory results and field experience. Extensive service records exist for conventional and epoxy-coated reinforcement. Those service records serve as the principal source for estimating the life of bridges using these types of reinforcement. The current laboratory results are used to supplement field experience. On the other hand, laboratory tests provide the principal source for estimating life expectancy of bridges containing the new corrosion-resistant reinforcing steels.

Cost effectiveness is evaluated based on a 75-year economic life using a discount rate of 2%, following techniques used by Kepler, Darwin, and Locke[3]. Comparisons are based on "out of pocket costs" for a 75-year economic life using bid tabulations and construction data from the States of Kansas and North Dakota from 1999 through 2001[3,4]. The evaluation includes current costs for bridge construction and reconstruction and experience-based estimates on the extent of required repairs. A uniform estimate of 25 years between subsequent repairs is used.

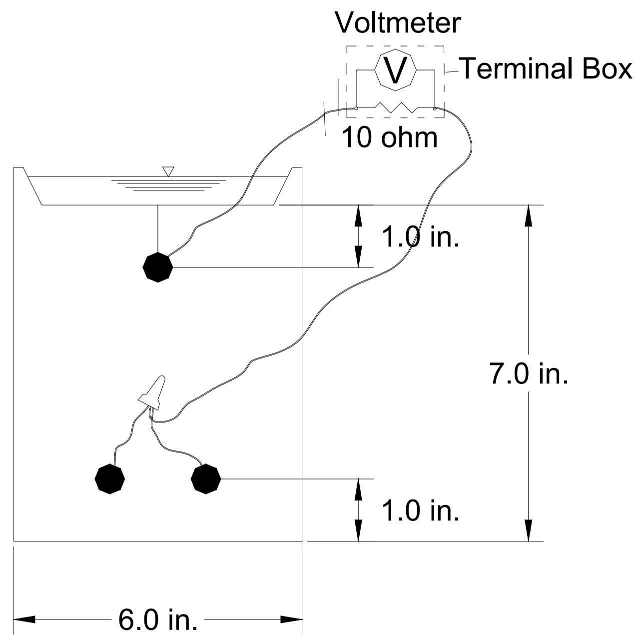



Fig. 3 Test Specimen for Cracked Beam Test[4]

## CORROSION TEST RESULTS

Most of the steels under study have undergone full macrocell tests, with both bare and mortar-wrapped bars, and bench-scale (Southern Exposure and cracked beam) tests through at least 48 weeks. The exception is the prototype stainless steel-clad bars, which have only undergone macrocell testing. For the comparisons that follow, emphasis is placed on corrosion rate, rather than on the chloride concentration needed to initiate corrosion. The reason is that measurements of chloride concentrations at cracks in reinforced concrete bridge decks show that very high concentrations can be reached in 1-1/2 to 8 years[6]. As a result, steels with somewhat higher chloride corrosion thresholds have only a small advantage over other steels because corrosion rate, rather than corrosion threshold, has the greater effect on service life.

The results of the tests on the three microalloyed steels (CRPT1, CRPT2, and CRT) demonstrate a small, consistent advantage over conventional steel. The advantage, which ranges from 4 to 65% depending on the test, but which is typically around 10 percent, is not enough to justify production and use of the material. Therefore, results for the microalloyed steel are not presented in this paper. Emphasis, rather, is placed on steels that show larger reductions in corrosion relative to conventional steel, that is, steels that corrode at rates between 1/2 and 1/250 of the rate of conventional reinforcement. Overall, the corrosion rates range from fractions to tens of μm/yr. To place these rates in some perspective, it is generally agreed that concrete will crack when total corrosion has reached 25 μm[7]. Once a crack forms, concrete permeability increases rapidly, leading to easier access for the chlorides and rapid deterioration of the structure.

## MACROCELL TESTS

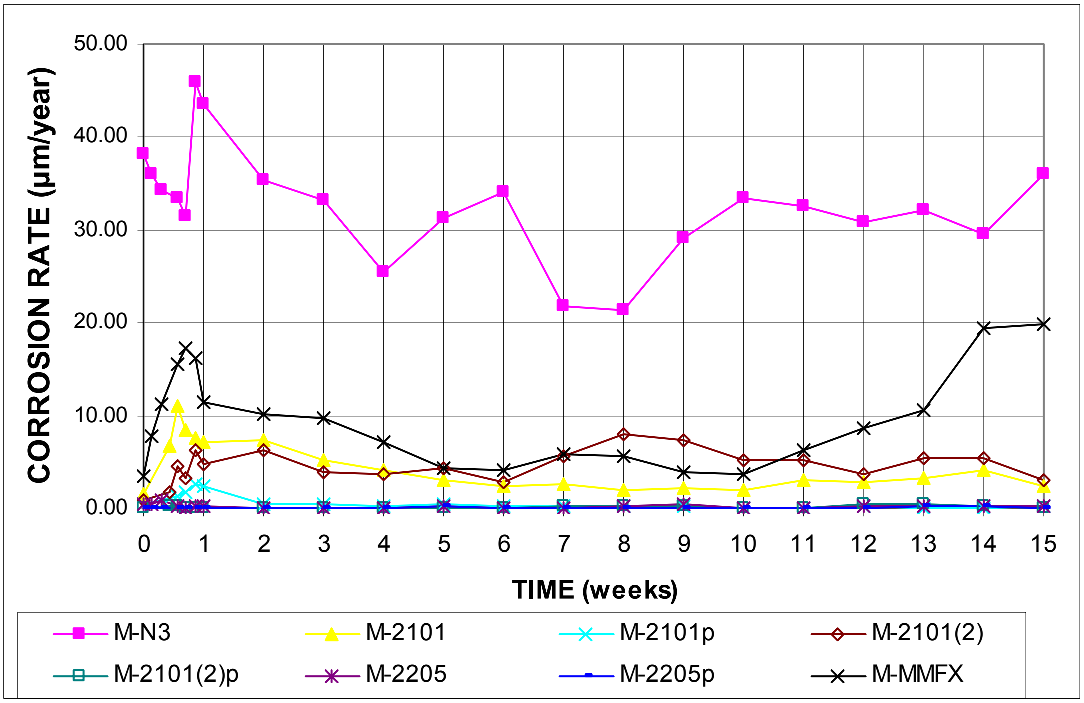
Macrocell tests were run on both bare and mortar-wrapped bars. The results for the bare bars are shown in Figs. 4a and 4b. The only difference between the figures is the scale of the vertical axis. Figure 4a shows the conventional steel (N3) corrodes at the highest rate (36 μm/yr) after 15 weeks, with MMFX steel reaching about 60% of that value. 2101 duplex steel [2101, 2101(2)] is corroding at about 3 μm/yr at the end of the test period. The other steels in the test, pickled 2101 [2101p, 2101(2)p], 2205, and pickled 2205 (2205p), are corroding at a rate of less than 0.25 μm/yr.

The results for the mortar-wrapped specimens are shown in Figs. 5a and 5b. In this case, two conventional steels (N2 and N3) complete the 15-week test with a corrosion rate of about 18 μm/yr, followed by MMFX steel at about 10.5 μm/yr, and 2101 at 5 μm/yr. Pickled 2101, 2205, and pickled 2205 steels corrode at a rate of approximately 0.10 μm/yr.

To date, only macrocell tests have been run on the stainless steel-clad (SC) reinforcement[8,9]. The reinforcing bars evaluated were prototype bars with a 304 stainless steel cladding. The results for bare bars, compared to conventional (N1) steel, are shown in Figs. 6a and 6b. As shown in Fig. 6b, the bare stainless steel-clad bars corrode at a rate of about 0.20 μm/yr per year. The results for the mortar-wrapped specimens are shown in Figs. 7a and 7b. In these tests, the conventional steel corrodes at a much lower rate than observed in the other tests, at only about 2 μm/yr. The stainless steel-clad bars corrode a rate of about 0.10 μm/yr.

## SOUTHERN EXPOSURE TESTS

The results for the Southern Exposure tests are shown in Figs. 8a and 8b. At 48 weeks, the Southern Exposure specimens containing conventional (N3) steel are corroding at a rate of about 6 μm/yr, as are the Southern Exposure specimens with conventional (N2) steel in the upper layer and 2205 duplex steel in the lower level. The latter specimens are used to measure potential galvanic effects. This is followed by MMFX steel, at about 2 μm/yr. Pickled 2101, 2205, and pickled 2205 steel corrode at less than 0.05 μm/yr (Fig. 8b). Tests of nonpickled 2101 are just getting under way; however, performance is expected to be similar to that observed in the macrocell tests, and therefore, nonpickled 2101 is not expected to be competitive with the pickled 2101 or the 2205 steels.




(a)

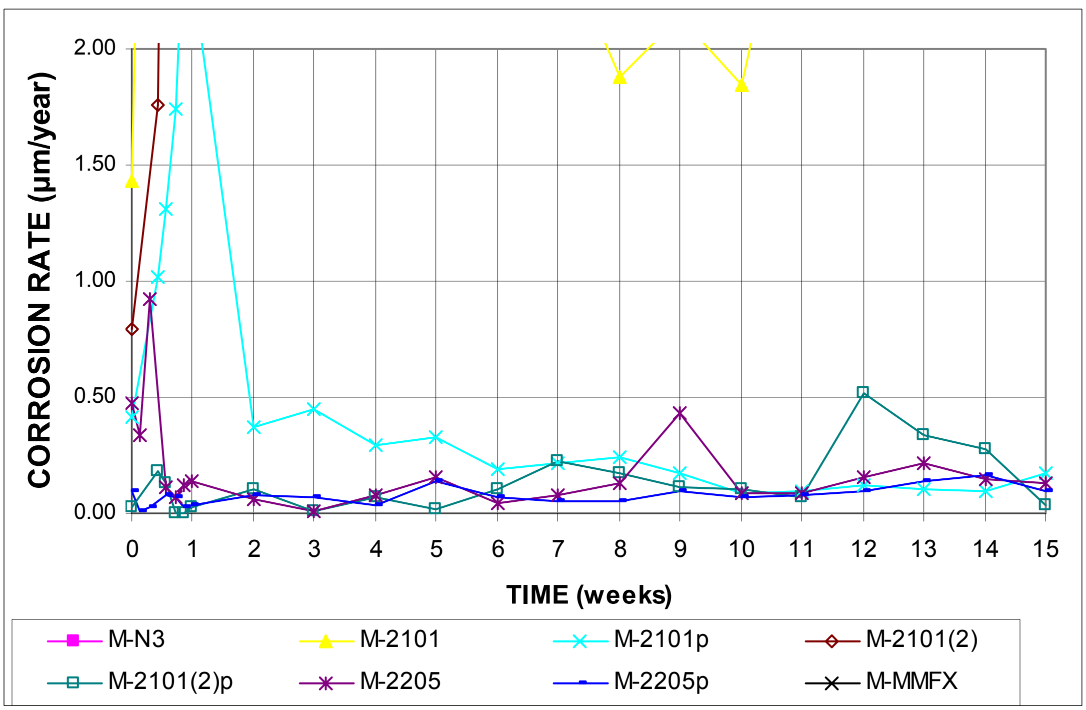



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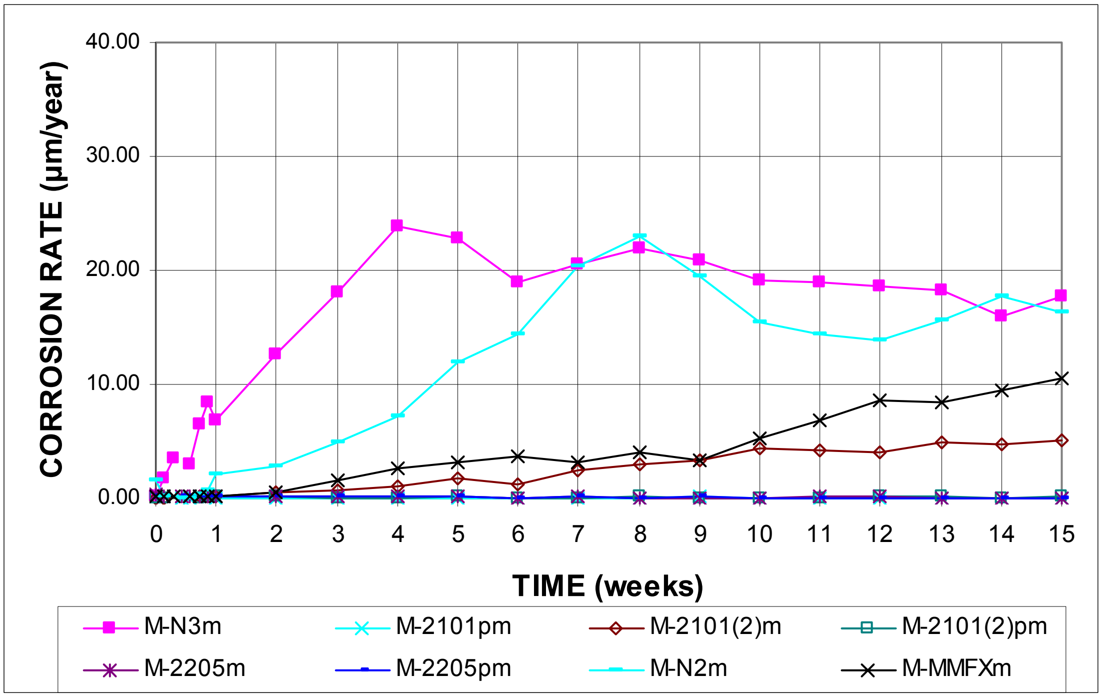
Fig. 4 Macrocell Test - Average corrosion rate. Bare specimens in 1.6 m ion NaCl

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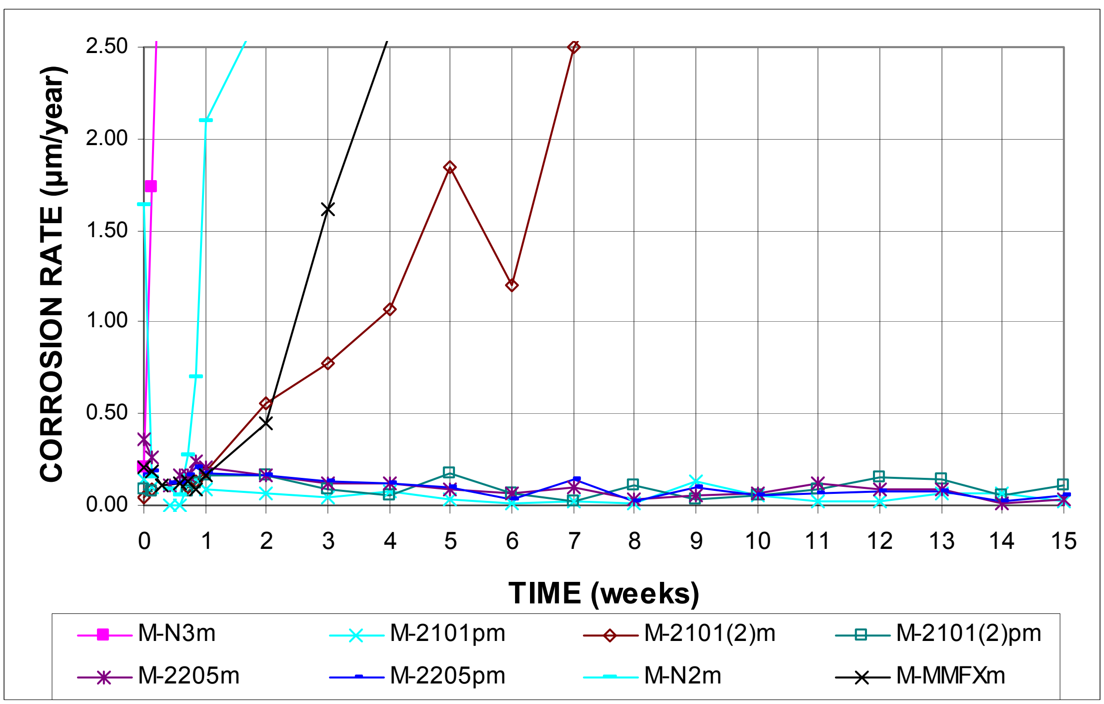
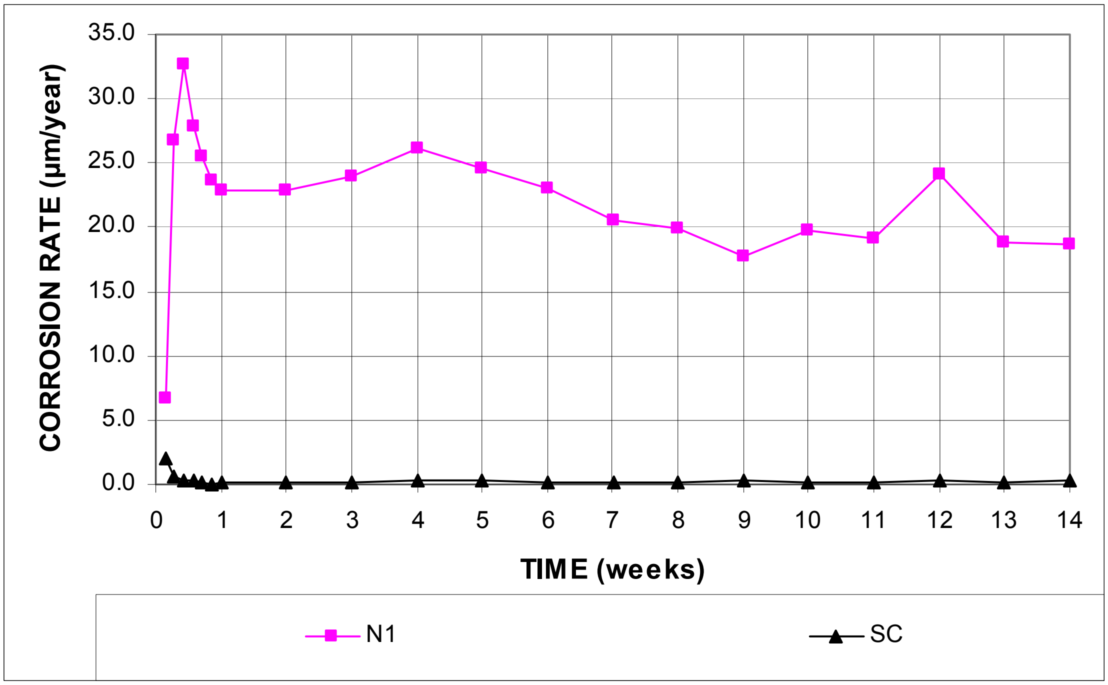



(b)

Fig. 5 Macrocell Test - Average corrosion rate. Mortar wrapped specimens with w/c=0.50 in 1.6 m ion NaCl.

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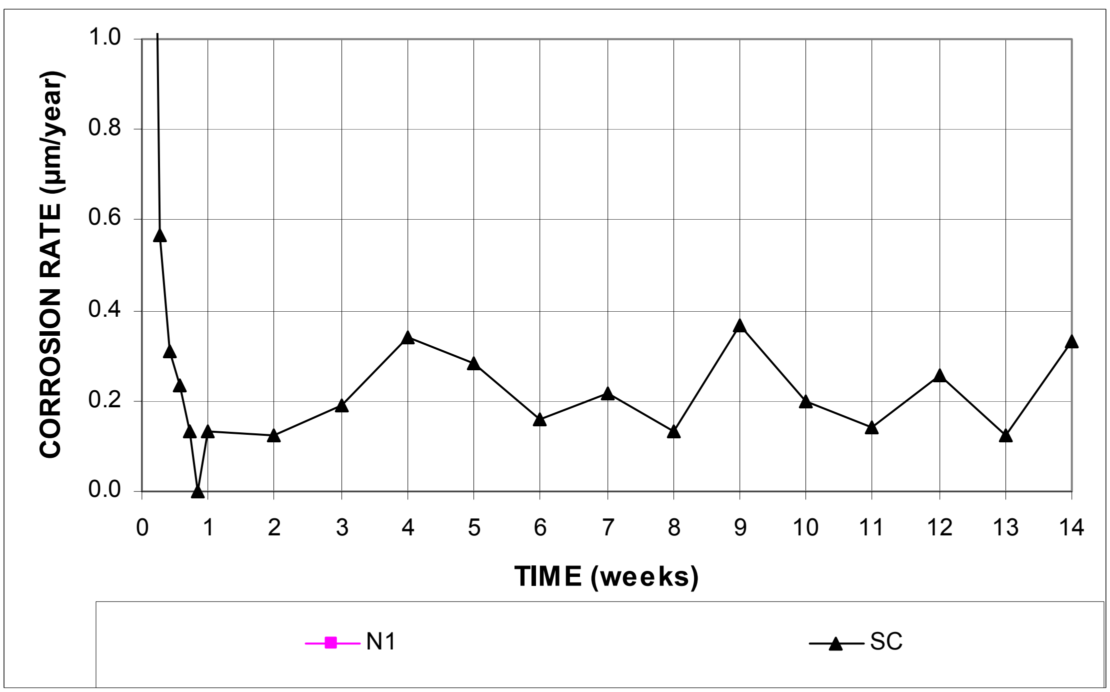
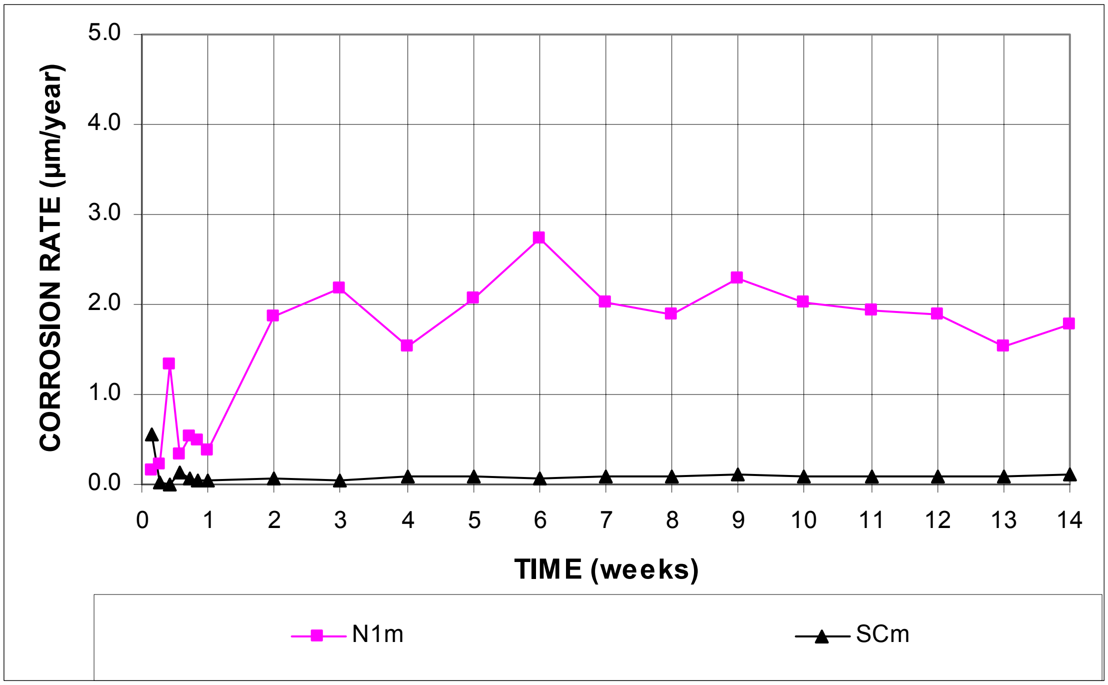



(b)

Fig. 6 Macrocell Test - Average corrosion rate.  Bare specimens in 1.6 m ion NaCl.
Conventional and stainless steel clad bars.

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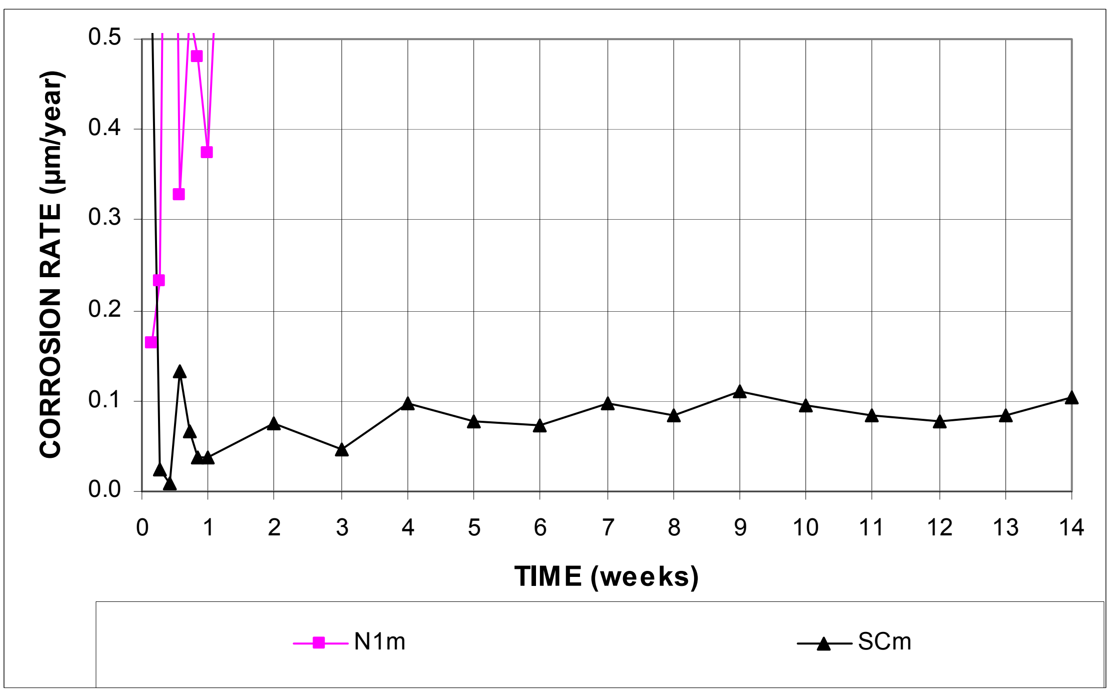
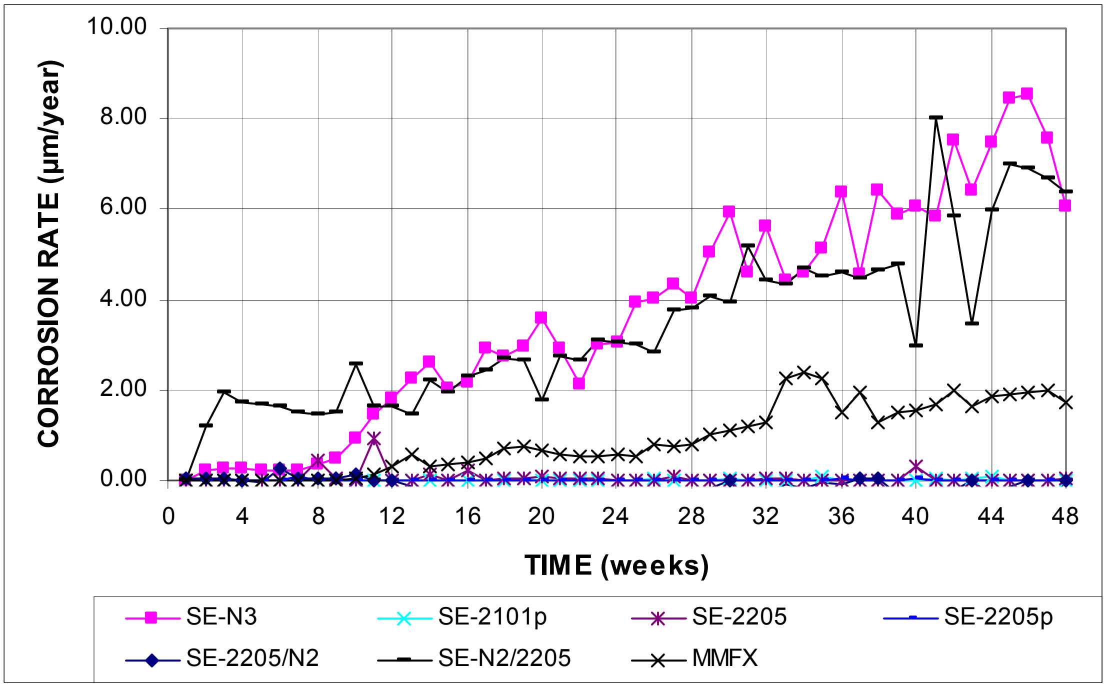



(b)

Fig. 7 Macrocell Test - Average corrosion rate. Mortar wrapped specimens with w/c=0.50 in 1.6 m ion NaCl. Conventional and stainless steel clad bars.

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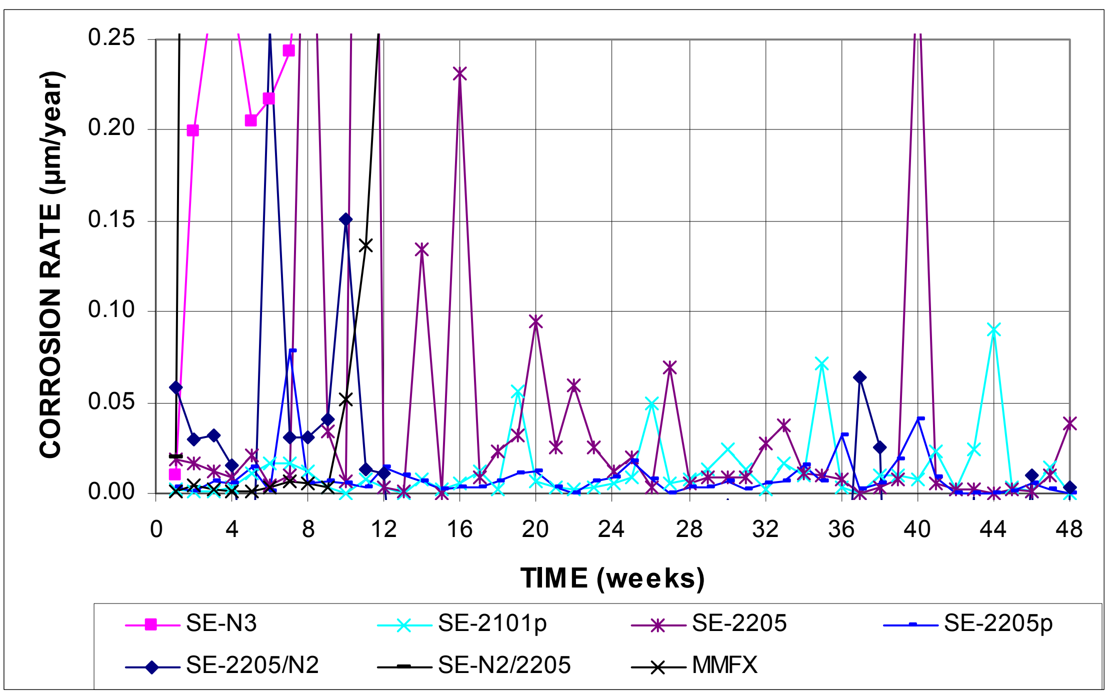



(b)

Fig. 8 Southern Exposure Test - Average corrosion rate, specimens with w/c=0.45, ponded with 15% NaCl solution.

### CRACKED BEAM TESTS

The results of the cracked beam tests are shown in Figs. 9a and 9b. As shown in Fig. 9a, the corrosion rate of conventional (N3) steel is relatively high (20 μm/yr) within the first four weeks, dropping to approximately 5 μm/yr through week 45. It then jumps to considerably higher corrosion rates, 18-30 μm/yr, in weeks 46 through 48. The high initial corrosion rate is due to the fact that the steel is directly subjected to the 15% NaCl solution. As time progresses, corrosion products fill the slot above the steel and the corrosion rate reaches a stable value. The recent increase may be due to an increase in thickness of corrosion products in some regions causing the concrete to crack, which allows additional chlorides to reach the steel. MMFX reinforcement exhibits the next highest corrosion rate, with a value of approximately 3 μm/yr. 2205 steel exhibits corrosion rates below 0.3 μm/yr (most often below 0.2 μm/yr), and pickled 2205 exhibits corrosion rates less than 0.05 μm/yr.

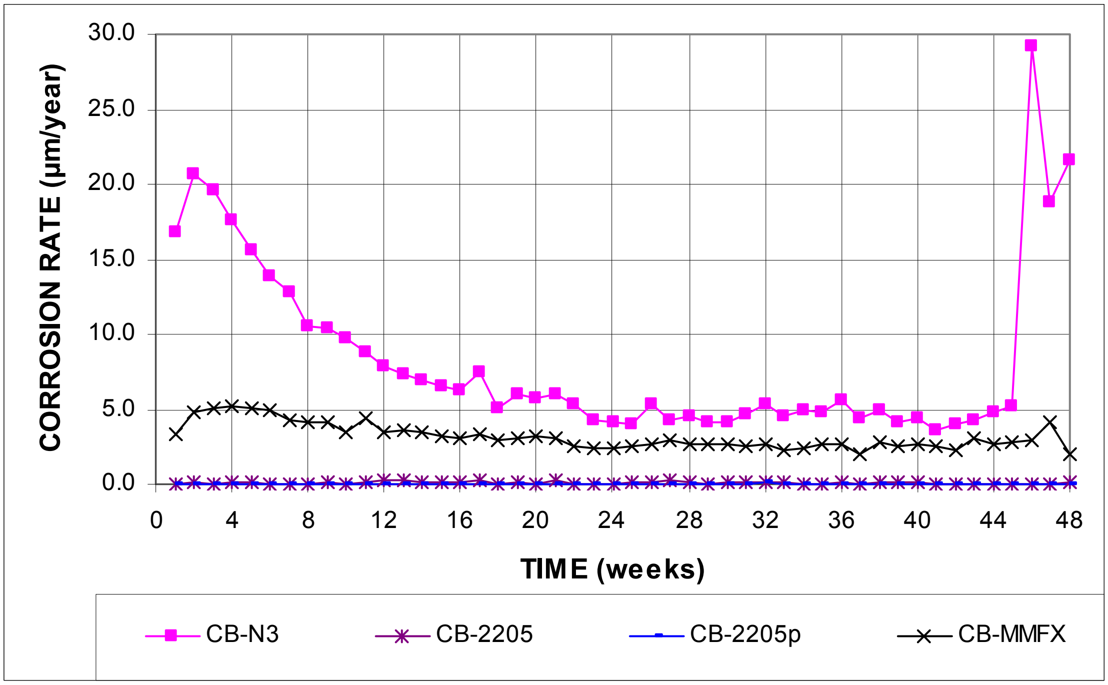
### SUMMARY OF TEST RESULTS

The test results described in this section indicate that the steels tested fall into distinct categories of corrosion resistance. As a general rule, for long-term protection of a reinforced concrete bridge deck with uncoated reinforcement, the corrosion rate should be no higher than 1/50 of conventional steel to justify its use as a replacement for epoxy-coated reinforcement, since at such a corrosion rate, it would require between 50 and 250 years to reach a corrosion loss of 25 μm. The prototype 304 stainless steel-clad reinforcement and the pickled 2101, nonpickled 2205, and pickled 2205 steels meet that criterion. The microalloyed, MMFX, and nonpickled 2101 steels do not.

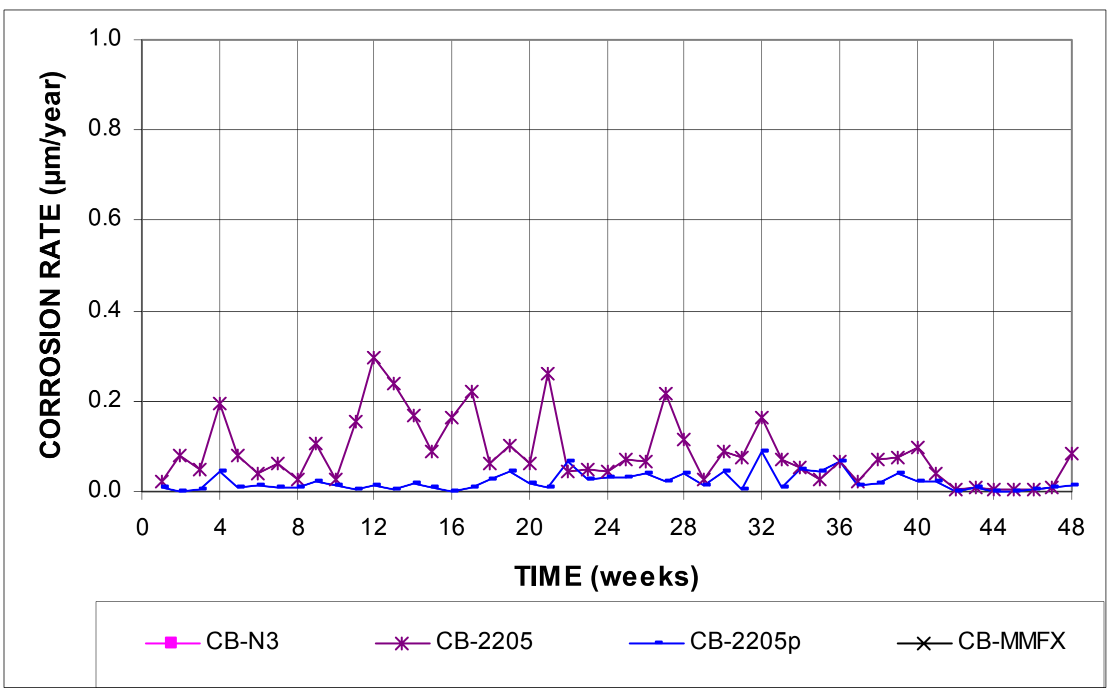
## LIFE EXPECTANCY AND COST EFFECTIVENESS

### LIFE EXPECTANCY

Based on laboratory test results reported here and elsewhere[4] bridge decks constructed with uncoated conventional steel will require repair in as little as 13 years, and decks containing MMFX microcomposite steel will require repair in about 27 years. In contrast, decks constructed with stainless steel and stainless steel-clad reinforcement will be able to provide a full 75 years without repair. Based on field experience in Kansas and South Dakota, decks constructed with uncoated conventional reinforcement will last 10 years in a harsh environment and 20 to 25 years in an arid environment; epoxy-coated steel will provide service between 30 and 40 years before first repair. The figures for epoxy-coated steel are estimates because the oldest bridges containing epoxy-coated steel have been in service only about 25 years old in the two states. The longer estimates are based on the observation that no bridges constructed with epoxy-coated reinforcement in either state have required repair due to the corrosion of the reinforcing steel.




(a)




(b)

Fig. 9 Cracked Beam Test - Average corrosion rate, specimens with w/c=0.45, ponded with 15% NaCl solution.

## COST EFFECTIVENESS

Comparisons of cost effectiveness are based on a bridge with a 150-ft span, 36-ft width, and 8.5-in. thick deck and are limited to out-of-pocket costs to maintain the bridge in service for 75 years. A summary of the costs on a square yard basis for the design used[4] are shown in Table 1. The figures are based on bid tabulations in Kansas and South Dakota. The cost in dollars/lb for each type of steel is based on the cost at the mill plus $0.44/lb for transportation and fabrication. The in-place costs for the reinforcement range from $0.59/lb for conventional steel to $1.44/lb for stainless steel. The cost at the mill for MMFX, stainless steel, and stainless steel-clad reinforcement were provided by the producers.

Table 1 New Construction Costs

| Item | In-place Cost | Cost/yd$^2$ |
|---|---|---|
| Concrete | \$350/yd$^3$ | \$82.60 |
| Conventional steel | \$0.59/lb | \$29.30 |
| Epoxy-coated steel | \$0.60/lb | \$29.80 |
| MMFX steel | \$0.84/lb | \$41.70 |
| Stainless steel | \$1.44/lb | \$71.50 |
| Stainless steel-clad | \$1.22/lb | \$60.60 |

A summary of the total costs of new construction are presented in Table 2 and range from \$112/yd$^2$ for conventional steel to \$154/yd$^2$ for stainless steel. Decks constructed with epoxy-coated steel cost nearly the same as those constructed with conventional steel. MMFX steel, at \$124/yd$^2$, falls in the middle. Overall, stainless steel and stainless steel-clad reinforcement result in the highest cost of new construction; whereas conventional and epoxy-coated steel result in the lowest cost of new construction.

| Table 2 Total Costs for New Construction |
|---|
| Conventional steel – \$112/yd$^2$ |
| Epoxy-coated steel – \$112/yd$^2$ |
| MMFX steel – \$124/yd$^2$ |
| Stainless steel – \$154/yd$^2$ |
| Stainless steel-clad – \$143/yd$^2$ |

Repair costs are summarized in Table 3. The total cost of repair of \$204/yd$^2$.

Total out-of-pocket costs over the 75-year period are summarized in Table 4. The costs represent direct expenditures needed to keep the bridge in service over this period of time. Conventional steel is evaluated based on arid exposure. Epoxy-coated reinforcement is evaluated using times to initial repair of 35 and 40 years. MMFX steel is evaluated based on times to first repair of 27 and 35 years. Conventional, epoxy-coated, and MMFX microcomposite steel all require two repairs during the 75-year period. Decks with stainless steel and stainless steel-clad reinforcement require no repair. The present value of the out-of-pocket costs using a 2% discount rate indicates that the two forms of reinforcement that have the highest cost of new construction, stainless steel and stainless steel-clad, have the lowest total costs, at \$154/yd$^2$ and \$143/yd$^2$, respectively. The reason is that they do not require repair during the 75 years. The highest cost is for MMFX steel with an estimated time to first repair 27 years, at \$316/yd$^2$. That is lowered to \$288/yd$^2$, if first repair can be delayed to 35 years. Decks with epoxy-coated reinforcement that last 35 years to first repair cost \$276/yd$^2$. At 40 years to the first repair, the price drops to \$261/yd$^2$.

Table 3 Repair costs

| Item | Unit | Cost | Cost/yd$^2$ |
|---|---|---|---|
| Low Slump Dense Concrete Overlay | yd$^2$ | \$80.00 | \$80 |
| Bridge Rail Modification | linear ft | \$45.25 | \$23 |
| Approach Guard Rail | Lump sum | \$16,000 | \$27 |
| Approach Pavement | Lump sum | \$16,500 | \$28 |
| Mobilization | Lump sum | \$18,600 | \$31 |
| Traffic Control and Misc. | Lump sum | \$9,000 | \$15 |
| Total repair cost = \$204/yd$^2$ | | | |

Table 4 Total "Out of Pocket" Costs – 75 years

| Reinforcement | Time to repair (Years) 1 | 2 | 3 | Present value at 2% (\$/yd$^2$) |
|---|---|---|---|---|
| Conventional - Arid exposure | 25 | 50 | | \$312 |
| Epoxy-coated | 35 | 60 | | \$276 |
| | 40 | 65 | | \$261 |
| MMFX | 27 | 52 | | \$316 |
| | 35 | 60 | | \$288 |
| Stainless steel | | | | \$154 |
| Stainless steel-clad | | | | \$143 |

## CONCLUSIONS

Based on the tests summarized in this paper, it may be concluded that:

1. Microalloyed steel corrodes at about 90% of the rate of conventional steel.

2. MMFX steel corrodes at 1/3 to 2/3 of the rate of conventional reinforcement.

3. Stainless steel and stainless steel-clad reinforcement corrode at 1/50 to 1/250 the rate of conventional reinforcement.

4. Microalloyed steel is not recommended for use in reinforced concrete bridge decks.

5. MMFX steel is not as cost effective as epoxy-coated steel and should not be used as a direct replacement without the use of a supplementary corrosion protection system.

6. Pickled 2101, 2205 and pickled 2205 stainless steel and the prototype stainless steel-clad reinforcement appear to be more cost effective than epoxy-coated steel and can be used as a direct replacement.

## ACKNOWLEDGEMENTS

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