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Evaluation of Metallized Stainless Steel Clad Reinforcement

Study SD2002-16
Executive Summary

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DISCLAIMER

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16. Abstract

SMI-316 SC^{TM} stainless steel clad concrete reinforcement is evaluated for corrosion resistance, mechanical properties, life expectancy, and cost effectiveness and compared with conventional mild steel reinforcement and epoxy-coated reinforcement (ECR). Corrosion performance is evaluated using rapid macrocell, Southern Exposure, and cracked beam tests. MMFX Microcomposite reinforcement is evaluated for the chloride content required for corrosion initiation, which is used to supplement corrosion test results from earlier research. Life expectancy and cost effectiveness of bridge decks containing the different reinforcing systems are evaluated using laboratory results for the chloride content required for corrosion initiation and rate of corrosion along with field experience and costs in South Dakota.

The SMI-316 SC bars satisfy the mechanical properties specified by ASTM A 615 for Grade 60 reinforcing bars. The SMI-316 SC bars should be fabricated (bent) using protective equipment similar to that used for epoxy-coated bars to limit damage to the cladding. Cladding thickness is satisfactory for normal construction operations. The corrosion rates of both SMI-316 SC and ECR reinforcement are less than 0.4% or 1/250 of that for conventional reinforcement. Epoxy-coated reinforcement embedded in concrete can undergo a significant loss of bond between the epoxy and the reinforcing steel, although total corrosion losses are low compared to those observed for conventional reinforcement. Bridge decks containing SMI-316 SC reinforcing steel will not require repair due to corrosion-induced concrete cracking during a 75-year service life. In comparison, conventional bridge decks require repair 10 to 25 years after the construction, depending on exposure conditions. Bridge decks containing epoxy-coated reinforcement will not require repair due to corrosion-induced concrete cracking during a 75-year service life but are estimated to require repair approximately 40 years after construction due to corrosion near damaged areas where the bond between the epoxy and reinforcing steel has been lost. Bridge decks containing SMI-316 SC reinforcing steel are cost-effective compared to bridge decks containing epoxy-coated reinforcement. The critical chloride corrosion threshold for MMFX Microcomposite steel is three to four times the corrosion threshold for conventional reinforcement, and the corrosion rate is approximately one-half that of conventional steel. Bridge decks containing MMFX Microcomposite reinforcing steel will require repair due to corrosion-induced concrete cracking approximately 33 years after construction and do not appear to be cost-effective when compared to bridge decks containing epoxy-coated reinforcement.

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EXECUTIVE SUMMARY

1. PROBLEM DESCRIPTION

The annual cost for maintenance and replacement of highway structures due to the corrosion of reinforcing steel is measured in billions of dollars in the United States. The principal cause of the corrosion is the diffusion of deicing chemicals into the concrete surrounding the steel. The average annual direct cost of corrosion of highway bridges is estimated at $8.3 billion, with indirect costs to users due to traffic delays and lost productivity estimated to be more than 10 times that value. As a result, techniques to significantly reduce or halt chloride-induced corrosion have been pursued aggressively for well over 30 years.

For most applications, especially bridge decks, the corrosion protection system of choice consists of a combination of epoxy-coated reinforcement (ECR) and increased concrete cover over the reinforcing bars. There are, however, some concerns about the combined system. The increased concrete cover increases the bridge self weight and the cost of construction. And, if poorly adhering epoxy coatings are used on the reinforcement, corrosion problems may be increased. These problems include imperfections in the coating that cause disbondment between the coating and the steel. Even if the coating has no local defects, water and, to a lesser extent, oxygen and chloride ions, may penetrate the epoxy, which may result in corrosion. This has happened for poorly applied coatings in substructures in Florida. Even properly applied coatings will lose adhesion over time, which means that coatings can deteriorate to an extent that prevents the epoxy from protecting the reinforcement once chlorides have reached the reinforcing steel.

As a result of these concerns, a number of other protective measures have been developed or are under development. These include the use of denser concretes, corrosion inhibitors, and corrosion-resistant steel alloys. Among the latter are 316LN stainless steel clad reinforcement (SMI-316 SC^{TM}), manufactured using a metallizing technique called the Osprey Process, and MMFX Microcomposite reinforcement.

To produce SMI-316 SC steel, stainless steel is sprayed on a mild steel billet. In the spraying and subsequent rolling process, the coating forms a metallic bond with the base metal. The surface of the steel is then blasted and pickled with acid to remove mill scale and other oxidation products. Based on earlier studies, the new steel should be less susceptible to corrosion than either conventional or epoxy-coated reinforcement (ECR) and should significantly limit corrosion caused by deicing salts throughout the life of the bridge deck.

MMFX Microcomposite steel is a high-strength, low carbon alloy with a chromium content of about 9% alloy (in practice, the range can be 8 to 10.9%) and a yield strength in excess of 100 ksi. The alloy was evaluated in an earlier study for the South Dakota Department of Transportation (SD2001-05) and found to be more corrosion resistant than conventional steel but less corrosion resistant than epoxy-coated reinforcement. Some questions remained after that study, which are addressed in the current report.

This report describes work to compare the performance of stainless steel clad reinforcement and MMFX Microcomposite steel with that of conventional and epoxy-coated reinforcement. The goal of this research is to determine the ability of these systems to slow the initiation of corrosion and lengthen the corrosion period.

2. OBJECTIVES

The research program has four objectives. They are to:

1) Determine the corrosion resistance of SMI-316 SC^{TM} steel compared to ECR reinforcement.
2) Determine the mechanical properties, quality, and suitability of SMI-316 SC^{TM} steel for use in bridge decks.
3) Estimate life expectancy and cost effectiveness of SMI-316 SC^{TM}, ECR, and mild steel reinforcement in South Dakota.
4) Obtain additional data on the corrosion performance of MMFX Microcomposite steel and formulate changes in Conclusions and Recommendations to SDDOT as appropriate.

The selection of a new reinforcing material for concrete bridge decks should be based on its ability to improve the life expectancy and cost effectiveness of the structural system. To be selected, the new material must provide a significant improvement in corrosion resistance compared to the current material of choice, epoxy-coated reinforcement (ECR), and serve as a structural replacement for the conventional mild steel reinforcement used to manufacture ECR. To this end, SMI-316 SC steel is compared based on corrosion-resistance with conventional mild steel reinforcement and ECR using rapid macrocell, Southern Exposure, and cracked beam tests and based on mechanical properties with conventional mild steel reinforcement using the tests used to qualify reinforcing steel in U.S. practice.

The results of the corrosion evaluation are combined with construction and maintenance experience in South Dakota and other states to evaluate the impact of SMI-316 SC reinforcing steel on the life expectancy and cost effectiveness of reinforced concrete bridge decks.

MMFX Technologies Corporation objected to some of the conclusions reached in an earlier report, SD2001-05-F, with special attention to the chloride thresholds at corrosion initiation for conventional and MMFX Microcomposite steel. Additional tests are used to update the current understanding of the corrosion resistance, life expectancy, and cost effectiveness of MMFX steel.

3. FINDINGS

A series of tasks were completed to evaluate the performance of SMI-316 SC and MMFX Microcomposite steel. The principal results of that research are summarized in this section.

3.1 Literature Search

Tests of a prototype of SMI-316 SC reinforcement, consisting of conventional steel clad with 304 stainless steel, indicated that the prototype reinforcement exhibited superior corrosion resistance compared to conventional reinforcing steel but that it required adequate protection at cut ends, where the mild steel core is not covered by cladding. Bare stainless steel clad bars corroded at about 1/100 of the rate for conventional mild steel bars. Bars embedded in mortar corroded at 1/20 to 1/50 of the rate for conventional bars. The early tests were limited to rapid macrocell tests, and longer-term tests were recommended.

Structural Metals Inc. remains in the development stage for the SMI-316 SC reinforcement and has not yet begun regular production of the bars. As a result, SMI-316 SC reinforcement has not been used in practice, with the exception of a single bridge over a tidal inlet on Johns Island, South Carolina, which was completed on May 23, 2005. In addition to SMI-316 SC bars, the bridge includes solid stainless, MMFX, epoxy-coated, and conventional steel reinforcement. Due to its short time in service, no observations are available on any of the reinforcing systems used in the bridge.

3.2 Mechanical Tests and Cladding Uniformity

Samples of conventional and SMI-316 SC reinforcing steel were tested to determine tensile and bend properties, and SMI-316 SC bars were evaluated for cladding uniformity and thickness variation.

Stress-strain and bend tests were performed for conventional and SMI-316 SC No. 5 and No. 6 bars. All bars met the requirements of ASTM A 615 for yield strength, tensile strength, and elongation, and all bars satisfied the bend requirements. The tests demonstrate that No. 5 and No. 6 SMI bars satisfy the mechanical properties required by ASTM A 615 and can be used as replacements for conventional No. 5 and No. 6 bars.

SMI-316 SC bars were sectioned and evaluated for cladding uniformity and thickness variation using a scanning electron microscope (SEM). Micrographs obtained using the SEM demonstrate that a metallurgical bond is obtained between the 316LN stainless steel cladding and the mild steel core of the bars. No unclad regions or cracks through the cladding were observed. Average cladding thicknesses varied between 26 and 30 mils (1 mil = 0.001 in.), with standard deviations between 8 and 13 mils for the No. 5 bars, and between 24 to 45 mils, with standard deviations between 6 and 13 mils for the No. 6 bars. The minimum cladding thickness measured on any bar was 6 mils, which is adequate to physically protect the core during normal construction operations.

3.3 Corrosion Tests of SMI-316 SC Reinforcement

The corrosion performance of SMI-316 SC, conventional, and epoxy-coated reinforcement was compared using No. 5 bars in rapid macrocell and longer-term bench-scale tests.

In the rapid macrocell test, either a bare or mortar-covered (wrapped) reinforcing bar is placed in a container containing simulated concrete pore solution and a preselected concentration of sodium chloride. Two similar specimens are placed in a second container containing simulated pore solution. The specimens are electrically connected across a 10-ohm resistor and the solutions are connected with a salt bridge. The specimen subjected to chlorides (the anode) represents the top layer of a bridge deck, while the specimens in the other container (cathode) represent the bars in the bottom layer of a bridge deck. Air is supplied to the liquid surrounding the cathode to ensure an adequate supply of oxygen. The corrosion rate, measured in micrometers per year (μm/yr), is determined based on the current in the system, which can be determined based on the voltage drop across the resistor, and the total corrosion loss, measured in μm, can be calculated by numerically integrating the corrosion rate over time. Corrosion losses for bare and mortar-wrapped bars are shown in Figures 1.1 and 1.2, respectively. The bare bar tests include conventional steel (Conv.), epoxy-coated steel with four $^1/_8$-in. diameter holes drilled through the epoxy (ECR), SMI-316 SC bars with no holes in the cladding and with ends of the bars protected by a cap filled with epoxy (SMI), SMI bars with four $^1/_8$-in. diameter holes drilled through the cladding with ends of the bars protected by a cap filled with epoxy (SMI-d), SMI bars with no holes in the cladding but *without* the ends of the bars protected by a cap filled with epoxy (SMI-nc), and SMI bars with a 180° bend, without holes and with end caps (SMI-b), all tested using a 1.6 m ion concentration of NaCl at the anode. The mortar-wrapped tests include the same series with the exception of the bent bars.

The figures show that ECR and SMI bars corrode at just a fraction of the rate of conventional steel, even if the epoxy or stainless steel cladding is damaged. For the bare bar tests shown in Figure 1.1, at 15 weeks, the ECR bars have losses under 6% of that for conventional reinforcement. The SMI and SMI-b bars have losses well below 0.1% of that for conventional steel, while the corresponding values for the SMI-d and SMI-nc bars are 1.0 and 0.2%, respectively. For the mortar-wrapped bar tests shown in Figure 1.2, the losses for ECR and SMI are less than 0.05% of that for conventional steel, with the SMI-d and SMI-nc bars showing losses equal to 0.5 and 0.25%, respectively, of that for conventional steel. In mortar, the ECR bars exhibit lower losses than the SMI-d bars, even though both have four $^1/_8$-in. diameter holes through the coating or cladding, because of the high resistivity of the epoxy coating, which limits the bar area that can serve as a cathode (limiting the rate of the overall reaction), while the full area of the SMI bars is conductive and can, thus, serve as a cathode.

The longer-term corrosion performance of reinforcing steel is measured using Southern Exposure and cracked beam tests. The specimens used in these tests are 7-in. deep slabs with two layers of steel that represent portions of bridge decks. The Southern Exposure specimen represents deck regions with intact concrete, and the cracked beam specimen represents regions in which the top layer of steel is exposed due to settlement and drying-induced shrinkage cracks. A 15% sodium chloride solution is ponded on the surface of the slabs, and the specimens are subjected to cycles of wetting and drying, which raises the chloride concentration within the concrete. In addition to evaluating corrosion performance, the results of the tests are used in the economic analysis.

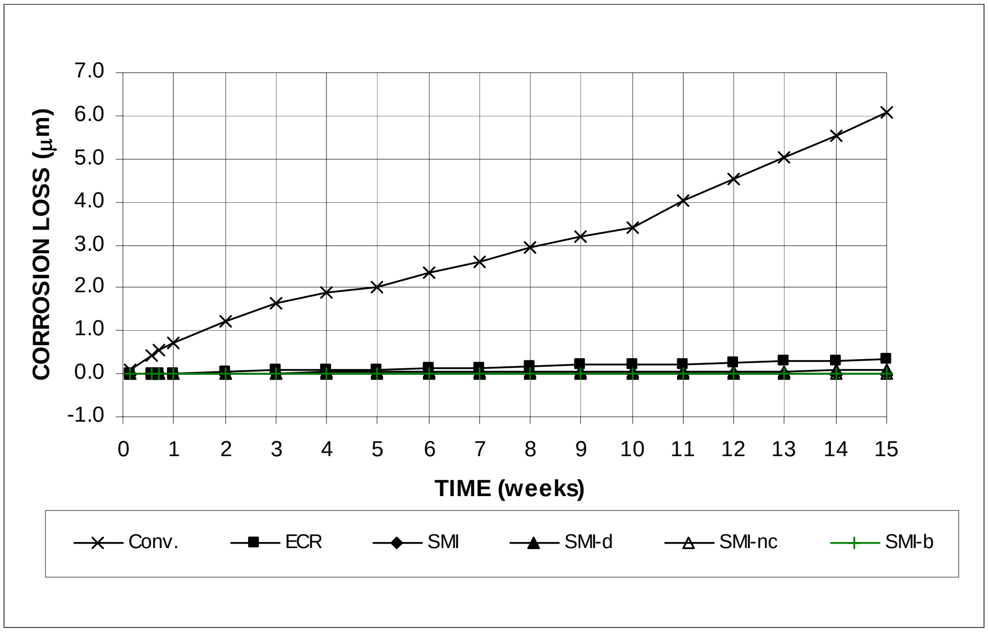

Figure 1 – Macrocell Test. Average corrosion loss versus time. Bare bars in NaCl and simulated concrete pore solutions.

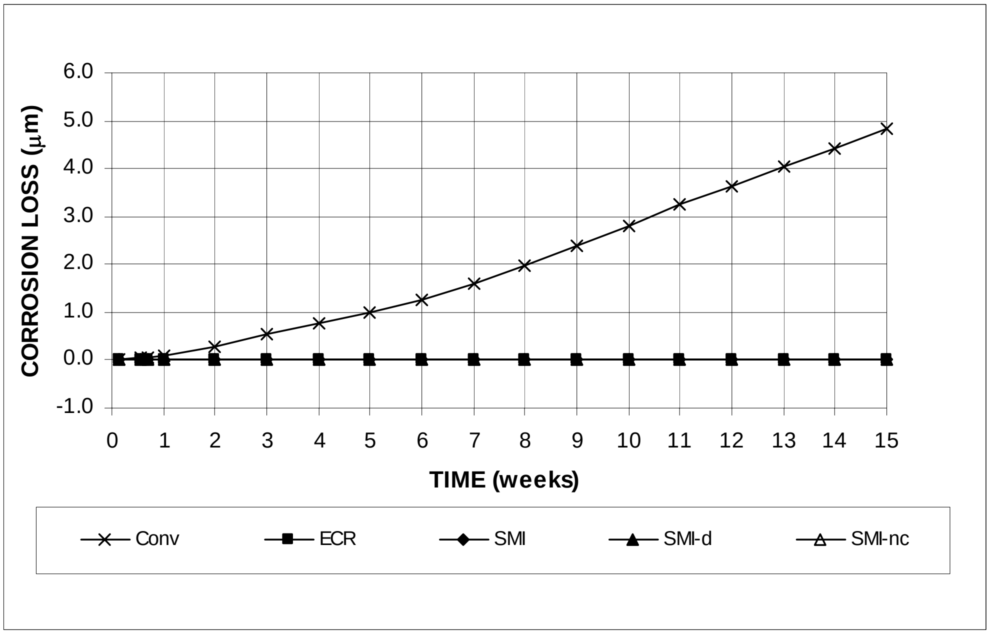

Figure 2 – Macrocell Test. Average corrosion loss versus time. Mortar-wrapped bars in NaCl and simulated concrete pore solutions.

The key results for the Southern Exposure and cracked beam tests are summarized in terms of total corrosion loss, in micrometers, in Figures 1.3 and 1.4, respectively. The Southern Exposure tests are used to evaluate straight conventional (Conv.), epoxy-coated (coating breached by four $^1/_8$-inch diameter holes) (ECR), SMI-316 SC reinforcing steel with no damage to the cladding (SMI), and SMI bars with four $^1/_8$-inch diameter holes drilled through the cladding (SMI-d). Additional Southern Exposure tests are used for two sets of specimens combining SMI and conventional steel to evaluate galvanic effects. One set is configured with SMI bars in the top mat and conventional steel in the bottom mat (SMI/ Conv.), while in the other set, the position of the steels is reversed (Conv./SMI). One more set of specimens is used to evaluate bent SMI bars (SMI-b). The bending equipment used did not have a protective coating, which resulted in damage to the cladding. Cracked beam tests are used to evaluate Conv., ECR, SMI, and SMI-d bars.

A comparison of Figures 1.3 and 1.4 illustrates the effect of concrete cracking on corrosion rate, with the conventional steel Southern Exposure specimens exhibiting six times the corrosion loss of the corresponding cracked beam specimens. Figure 1.3 also shows that combining SMI-316 SC with conventional reinforcement has little apparent effect on the corrosion rate of either material. As observed for the rapid macrocell tests, Figures 1.3 and 1.4 illustrate that ECR and SMI steel, damaged or not, corrode at a fraction of the rate of conventional steel, with the ECR and SMI bar specimens exhibiting losses equal to less than 0.4% (1/250) of that for conventional steel specimens in either test. The losses for the SMI-d and damaged SMI-b specimens equal 4.5% and 2%, respectively, of the losses observed for conventional steel. The damage that occurred during the bending operation emphasizes the importance of using fabrication equipment of the type now used for epoxy-coated bars that will not damage the cladding when the bars are bent.

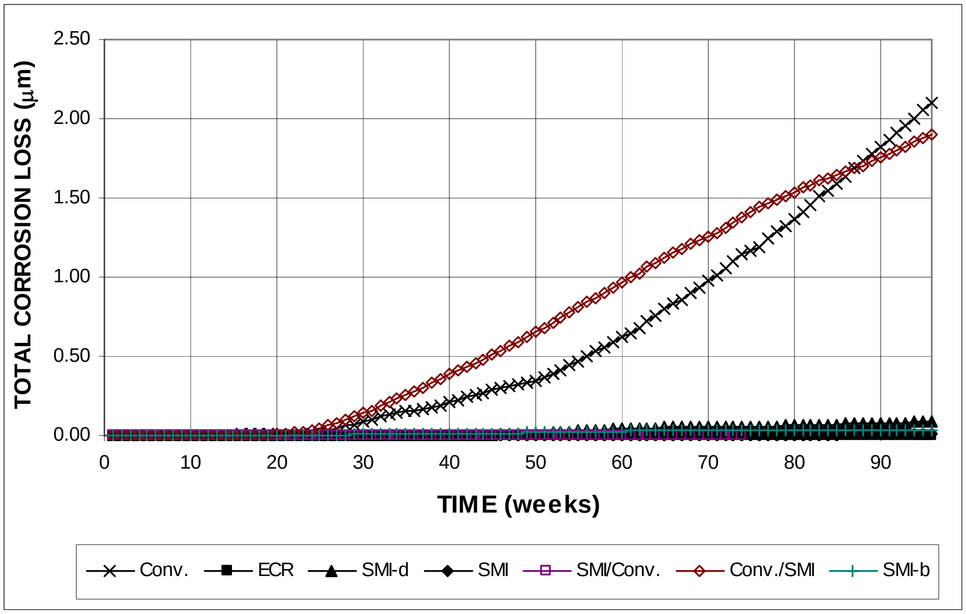

Figure 3 – Southern Exposure Test. Average total corrosion loss versus time.

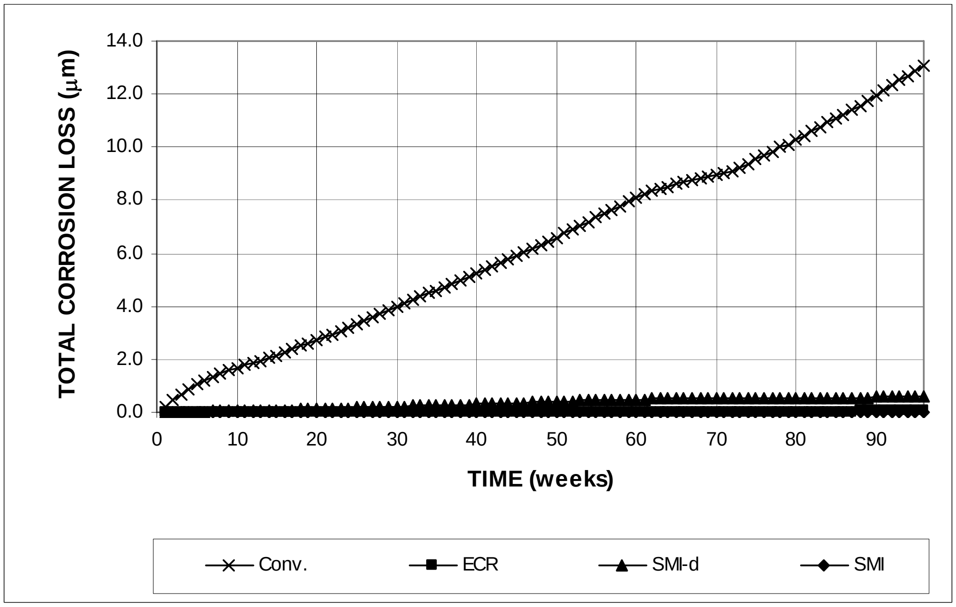

Figure 4 – Cracked Beam Test. Average total corrosion loss versus time.

3.4 Corrosion Tests of MMFX Microcomposite Reinforcement

For MMFX reinforcement, the key task was to establish the critical chloride corrosion threshold, that is the chloride concentration in concrete that causes the reinforcement to begin to corrode. Earlier studies had established the value to be between 1 and 2 lb/yd^3 for conventional steel and between 3 and 8 lb/yd^3 for MMFX Microcomposite steel.

The current study found the critical chloride threshold for conventional steel to be between 0.90 to 2.21 lb/yd^3, with an average of 1.75 lb/yd^3, based on water-soluble chlorides. The critical chloride threshold for MMFX Microcomposite steel ranged from 4.5 to 9.2 lb/yd^3, with an average of 6.5 lb/yd^3. These values are combined with corrosion rates measured in this and earlier studies to determine the life expectancy of bridges containing these reinforcing materials.

These values are well below the threshold (concentrations in excess of 25 lb/yd^3) for 316LN stainless steel, which is used to clad SMI-316 SC reinforcement.

3.5 Life Expectancy and Economic Analysis

The life expectancy and cost effectiveness of bridges containing SMI-316 SC, MMFX Microcomposite, ECR, and conventional reinforcement are determined based on an analysis of laboratory results and the experience of the South Dakota Department of Transportation. Laboratory results in the current and earlier studies indicate that conventional reinforcement or exposed epoxy-coated reinforcement will begin corroding at an average chloride concentration of 1.75 lb/yd^3. The corresponding values for the stainless steel used as the cladding for SMI-316 SC steel and MMFX Microcomposite steel are more than 25 lb/yd^3 and 6.5 lb/yd^3, respectively. These values are used to estimate time-to-corrosion-initiation based on observed chloride contents in cracked bridge decks. One-half of the average of the corrosion rates after corrosion initiation in the Southern Exposure and cracked beam tests is used to estimate the time required to reach a total thickness loss of 25 µm (0.001 in.), the expected value that will result in concrete cracking due to the deposition of corrosion products adjacent to the bar.

Based on laboratory results, times to first repair of 12 and 33 years are calculated for conventional and MMFX steel, respectively. Stainless steel clad reinforcement will not require repair during the 75-year service life used to evaluate the cost-effectiveness of the reinforcing systems. Based on experience, SDDOT estimates of times to first repair for conventional reinforcement are 10 years under harsh conditions and 25 years under arid conditions. Time to first repair for epoxy-coated reinforcement is estimated to be 40 years based on the observation that no bridges built with epoxy-coated reinforcement in South Dakota have required repair due to corrosion of the reinforcing steel.

Using the time to first repair and a standard 25-year period for subsequent repairs, the cost effectiveness of conventional, epoxy-coated, SMI-316 SC, and MMFX reinforcement was evaluated using a typical 8.5-in bridge deck over a service life of 75 years at discount rates of 2, 4, and 6%. The analysis indicates that, at a discount rate of 2%, SMI-316 SC has the lowest present value cost, \$250/yd^2, which is equal to the initial cost alone, since no repairs are required. Next is epoxy-coated reinforcement, with either a 35 or a 40-year time to first repair, \$421 or \$399/yd^2, compared to \$441 for MMFX steel with a time to first repair of 33 years, and \$461/yd^2 for conventional steel for a time to first repair of 25 years and a cost of \$649/yd^2 for time to first repair of 10 years.

4. CONCLUSIONS

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

1. The No. 5 and No. 6 SMI-316 SC bars tested in this study satisfy the mechanical properties specified by ASTM A 615 and can be used as replacements for conventional No. 5 and No. 6 Grade 60 reinforcing bars. The steel, however, is not currently in production.

2. A metallurgical bond is obtained between the 316LN stainless steel cladding and the mild steel core of the SMI-316 SC bars. The average cladding thickness varied between 26 and 45 mils (0.026 and 0.045 in.). The minimum thickness measured at any location was 6 mils.

3. SMI-316 SC bars should be fabricated (bent) using protective equipment similar to that used for epoxy-coated bars. Without protection, there is significant potential for damage to the cladding. The minimum measured thickness of the cladding, however, is adequate for normal handling during construction.

4. The corrosion rate of SMI-316 SC reinforcement is less than 0.4% or 1/250 of that for conventional reinforcement. Total corrosion losses for SMI-316 SC bars were insignificant in the tests.

5. Corrosion losses for damaged epoxy-coated reinforcement were below those for damaged SMI-316 SC reinforcement. The difference results from the high resistivity of the

epoxy coating, which limits the bar area that can serve as a cathode, while the full area of the SMI-316 SC bars can serve as a cathode.

6. Epoxy-filled plastic caps protect the cut ends of SMI-316 SC reinforcement from corrosion.

7. Epoxy-coated reinforcement embedded in concrete can undergo a significant loss of bond between the epoxy and the reinforcing steel when subjected to high moisture and high chloride concentrations. Corrosion products form under the coating, although total corrosion losses are low compared to those observed for conventional reinforcement.

8. Similar corrosion products are deposited on conventional reinforcing steel and on the mild steel core at damaged regions of SMI-316 SC steel.

9. Bridge decks containing SMI-316 SC reinforcing steel will not require repair due to corrosion-induced concrete cracking during a 75-year service life. In comparison, conventional bridge decks require repair 10 to 25 years after the construction, depending on exposure conditions. Bridge decks containing epoxy-coated reinforcement will not require repair due to corrosion-induced concrete cracking during a 75-year service life but are estimated to require repair approximately 40 years after construction due to corrosion near damaged areas where the bond between the epoxy and reinforcing steel has been lost.

10. Bridge decks containing SMI-316 SC reinforcing steel are cost-effective compared to bridge decks containing epoxy-coated reinforcement.

11. The critical chloride corrosion threshold for MMFX Microcomposite steel is three to four times the corrosion threshold for conventional reinforcement. The corrosion rate for MMFX steel is approximately one-half that of conventional steel.

12. Bridge decks containing MMFX Microcomposite reinforcing steel will require repair due to corrosion-induced concrete cracking approximately 33 years after construction.

13. Bridge decks containing MMFX Microcomposite steel do not appear to be cost-effective when compared to bridge decks containing epoxy-coated reinforcement.

5. IMPLEMENTATION RECOMMENDATIONS

The evaluation and test results presented in this report lead to the following implementation recommendations.

1. SMI-316 SC stainless steel clad reinforcement is recommended as a cost-effective direct replacement for epoxy-coated reinforcement. Cut ends of the bars should be protected with a system such as plastic caps filled with epoxy and the bars should be protected from damage to the cladding during bending operations.

This recommendation is based on observations that SMI-316 SC stainless steel clad reinforcement corrodes at a negligible rate when subjected to high moisture and chloride conditions. Based on field test results for chlorides in bridge decks, it is highly unlikely that the critical chloride corrosion threshold of the stainless steel cladding will be reached in less than 100 years in bridge decks. The corrosion performance of SMI-316 SC steel will equal or exceed that of epoxy-coated reinforcement as long as the ends of the bars are protected, such as with plastic caps filled with epoxy, and steps are taken, as they are for epoxy-coated reinforcement, to protect the bars from damage to the cladding during fabrication (bending). Normal handling will not result in damage to the cladding. Acid pickling to remove mill scale and other oxidation products will be needed to achieve the corrosion resistance obtained in this study by the SMI-316 SC stainless steel clad bars. The initial cost for construction with SMI-316 SC reinforcement is higher than that for epoxy-coated or conventional reinforcement, but because it requires no repair, the lifetime cost is significantly less.

2. MMFX Microcomposite reinforcing steel should not be used as a direct replacement for epoxy-coated reinforcement without the use of a supplementary corrosion protection system. Use of the material in its current form is not recommended for reinforced concrete bridge decks in South Dakota.

This recommendation matches that reported in SD 2001-5 and is based on observations that, while MMFX reinforcing steel has a higher corrosion threshold and corrodes at a lower rate than conventional reinforcement, (1) its corrosion-resistance properties are not superior to that of epoxy-coated reinforcement, and (2) bridge decks constructed with MMFX reinforcing steel will have a higher initial cost, a shorter life expectancy, and a higher lifetime cost than bridge decks constructed with epoxy-coated reinforcement.