11-1-2000

Application of Stainless and Stainless-Clad Reinforcing Bars in Highway Construction

J. Bower

L. Friedersdorf

B. Neuhart

A. Marder

Recommended Citation

Bower, J.; Friedersdorf, L.; Neuhart, B.; and Marder, A., "Application of Stainless and Stainless-Clad Reinforcing Bars in Highway Construction" (2000). ATLSS Reports. ATLSS report number 00-10:.
http://preserve.lehigh.edu/engr-civil-environmental-atlss-reports/9

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

PENNDOT RESEARCH

APPLICATION OF STAINLESS AND STAINLESS-CLAD REINFORCING BARS IN HIGHWAY CONSTRUCTION

TRANSPORTATION MATERIALS PARTNERSHIP

AGREEMENT NO. 359631, WORK ORDER 4

FINAL REPORT

November 2000

By J. E. Bower, L. E. Friedersdorf, B. H. Neuhart, A. R. Marder, and A. I. Juda

PENNSTATE

1855

Pennsylvania Transportation Institute

The Pennsylvania State University
Transportation Research Building
University Park, PA 16802-4710
(814) 865-1891 www.pti.psu.edu

Technical Report Documentation Page

1. Report No.
FHWA-PA-2000-011+96-31 (04)

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

Application of Stainless and Stainless-Clad Steel Reinforcing Bars in Highway Construction

5. Report Date
November 27, 2000

6. Performing Organization Code

7. Author(s)
J.E. Bower, L.E. Friedersdorf, B.H. Neuhart, A.R. Marder, and A.I. Juda

8. Performing Organization Report No.

9. Performing Organization Name and Address
Lehigh University
27 Memorial Drive West
Bethlehem PA 18015-3090
via
The Pennsylvania Transportation Institute
Transportation Research Building
The Pennsylvania State University
University Park, PA 16802-4710

10. Work Unit No. (TRAIS)

11. Contract or Grant No. 359631

12. Sponsoring Agency Name and Address
The Pennsylvania Department of Transportation
Bureau of Planning and Research
555 Walnut Street, 6th Floor Forum Place
Harrisburg, PA 17101-1900

13. Type of Report and Period Covered

Final Report

14. Sponsoring Agency Code

15. Supplementary Notes
COTR:

16. Abstract

Increasing the durability of reinforced concrete systems for transportation structures has been a long-standing goal of federal and state transportation agencies. The strategy of increasing the corrosion resistance of the reinforcing material is common, with epoxy-coated carbon-steel reinforcing bars having a major share of the current market. However, one idea with growing support that overcomes troubles that some states have experienced with epoxy-coated bars is to apply stainless steel reinforcement, which has much higher inherent resistance to corrosion than other coated or uncoated bar systems. Therefore, an assessment was made for PennDOT of the past research, current applications, governing specifications, properties, cost factors, and competing systems that can affect the choice to use either solid stainless steel or stainless-clad steel reinforcement. It is concluded that the numerous field installations and laboratory studies, which have been conducted in about 30 states, Canada, and Europe, provide strong positive evidence that highway application of solid stainless reinforcement and, to a lesser extent, stainless-clad reinforcement would benefit PennDOT. Stainless and stainless-clad reinforcement would provide a high degree of corrosion resistance, extended pavement and bridge-deck life – even in heavy chloride environments–and reduced life-cycle cost. These gains are achievable without any sacrifice in mechanical and other properties, and require only the formulation of a specification by PennDOT that permits the use of stainless and stainless-clad reinforcement.

17. Key Words

Reinforcing bars, dowel bars, stainless steel, stainless clad steel, concrete, bridge deck, pavement

18. Distribution Statement
No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified		

Form DOT F 1700.7 **(8-72)** **Reproduction of completed page authorized**

APPLICATION OF STAINLESS AND STAINLESS-CLAD REINFORCING BARS IN HIGHWAY CONSTRUCTION

Transportation Materials Partnership
Agreement No. 359631
Work Order 4

FINAL REPORT

Prepared for

Commonwealth of Pennsylvania
Department of Transportation

By

J.E. Bower, L.E. Friedersdorf, B. H. Neuhart, A.R. Marder, and A.I. Juda
(Lehigh University, ATLSS File 00-10)

The Pennsylvania Transportation Institute
The Pennsylvania State University
Transportation Research Building
University Park, PA 16802-4710

November 2000

This work was sponsored by the Pennsylvania Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the Federal Highway Administration, U.S. Department of Transportation, or the Commonwealth of Pennsylvania at the time of publication. This report does not constitute a standard, specification, or regulation.

PTI 2001-13

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Significant support exists for ideas that increase the durability of reinforced concrete systems through the prevention of the corrosion of steel reinforcing bars. One idea with growing support is to increase the corrosion resistance of the reinforcing bars by selecting stainless and stainless-clad steel as the reinforcing-bar material. Such bars can provide attractive alternatives to epoxy-coated and other bar systems for numerous highway and bridge applications.

Studies to increase the durability of reinforced concrete systems for transportation structures have been and are being conducted or sponsored by numerous federal and state agencies. Almost 15 years ago, the Office of Technology Assessment in Washington, D.C., cited deterioration, through corrosion, of steel-reinforced concrete bridge decks as a "serious national problem," and called for furthering anticorrosion methods. The National Cooperative Highway Research Program (NCHRP), the Federal Highway Administration (FHWA), the Civil Engineering Research Foundation, industry groups, and state transportation agencies have since supported major research of various types of anticorrosion reinforcing bars. About 30 states, including Pennsylvania, are known or reported to be evaluating stainless or stainless-clad steel as anticorrosion concrete reinforcement. Outside of the United States, principally in Canada and the UK, numerous studies have been or are being conducted on the same issues.

Although a vast number of stainless steel alloys exist, stainless reinforcing bars are generally selected from only four or five relatively common austenitic grades or a duplex-alloy grade. The rationale is that these few can provide a desirable combination of corrosion resistance, price, and availability. The most common austenitic alloys are 304 (UNS No. S30400), 304 L (S 30403), 316 (S 31600), and 316 L (S 31603). The most common duplex alloy is 2205 (S 31803). Stainless-clad reinforcing bars are also generally produced using one of the above four austenitic grades as the cladding material. The mechanical properties of the stainless and stainless-clad steel bars are equivalent to those of "black" carbon steel bars so an exchange of bar material from carbon to stainless allows equivalent structural capacity.

Stainless reinforcing bars have a product cost up to about 6x that of "black" bars, on a $/lb. basis. For stainless-clad bars, the price ratio is only about 2x. These ratios reduce to 4x and 1.25x when stainless and stainless-clad bars are compared to epoxy-coated bars. Stainless steel rebars are readily available in all parts of the United States and Canada. Similarly, stainless steel dowel bars are readily available in the United States. Stainless-clad bars and stainless-clad dowels are currently only produced in the UK, but are aggressively marketed in the United States.

Standards for stainless steel concrete reinforcing bars are adequately provided by ASTM Designation A955M-96. This specification provides the same bar grades, bar designations, and bend requirements as A615M-96a for "black" carbon steel bars. An ASTM standard does not yet exist for stainless-clad bars, but a standards-development committee is reviewing a draft specification. At this time, neither American Association of State Highway and Transportation Officials (AASHTO) nor the Pennsylvania Department of Transportation (PennDOT) has material specifications explicitly for stainless or stainless-clad reinforcing; nor does the AWS Welding Code. However, several states and Canadian provinces have written material and

performance specifications for stainless and stainless-clad reinforcing appropriate to specific contracts and this approach might appeal to Pennsylvania.

Because stainless and stainless-clad reinforcing bars are relatively new products, there is a limited amount of data of a long-range nature about their performance. However, numerous examples are described herein as to how and where stainless and stainless-clad reinforcement has been or is being installed or evaluated. Pennsylvania's limited evaluations are included. These evaluations include many coastal applications (FL, HI, LA, MD, ME, NJ, OR, SC, and VA) where salt-contaminated concrete can occur. They include many northern or cold-weather sites (IL, IN, ME, MI, MN, NY, OH, WI, and ON) where de-icing or anti-icing salts are used. Finally, they include applications where dense traffic occurs (MI, NJ, ON), such as highway ramps, necessitating minimizing road closings for repairs. Other evaluations are more general in nature. However, the consistency in the evaluations, both with dowels and with rebars, is to achieve longer-life highways and bridge decks by making negligible the deterioration due to corrosion involving the reinforcing steel, and the evaluations are confirming the corrosion-resistance benefits.

Because the major benefit of stainless steel reinforcing is its corrosion resistance, this report includes a description the corrosion principles, corrosion experiments, and corrosion factors that affect its application. The report describes the roles of chlorides, of carbonation, and of acid rain and summarizes the numerous studies, mainly in the United States and Europe, of their corrosive effects. Similarly, studies of galvanic corrosion, including stainless steel reinforcing, are summarized because galvanic corrosion may occur in slabs where mixed steel reinforcing is used without appropriate isolation between the mixed steels. Electrochemical corrosion protection principles are also reviewed with emphasis on electrochemical realkalization. Electrochemical chloride extraction (ECE) is only briefly mentioned because Lehigh University has a separate project in PennDOT's Materials Partnership Program to study its benefits. The corrosion findings have been that austenitic stainless steels consistently out-perform other bars tested, including black, epoxy-coated, and other coated bars. Moreover, galvanic corrosion couples are slight with austenitic steels. Among the austenitic steels, the 316 alloys out-perform the 304 alloys in chloride resistance and galvanic couple resistance.

Another significant benefit of stainless steel rebars is their greater quality assurance. Whereas conventional black rebars and coated black rebars are generally low-grade carbon steel with limited chemistry control and generally no fracture-toughness control, stainless steel rebars are produced to specific chemistries and have considerable fracture toughness.

The higher product cost of stainless steel reinforcing has diminished importance when considered in terms of project and life-cycle cost. In one example in which stainless steel was simply substituted for "black" bars, a 5.5x higher product cost of stainless steel resulted in only a 1.18x higher project cost. Simple substitution of rebar material is generally not the appropriate design selection, however. Two life-cycle cost examples are cited and illustrate how the considerations that have been included in existing life-cycle-cost (LCC) software programs provide insight into material selections. In the two examples involving a need for a 75-year bridge-deck life, stainless reinforcing had a substantial benefit over both "black" and epoxy-coated carbon steel bars.

Epoxy-coated bars represent one competing corrosion-resistant reinforcing system. The report examines this system and several others, including bar systems such as galvanized rebars, FRP bars, and dual-phase steel bars, environmental systems such as deicing practices using calcium magnesium acetate (CMA), and concrete practices.

TEA 21 allocates significant sums of money for research and construction use of innovative materials, and these funds should encourage states to use higher quality, more corrosion-resistant systems like stainless steel and stainless-clad steel reinforcing to reduce the life-cycle cost of a highway project. The findings of this report suggest that Pennsylvania could move to stainless steel rebars and dowels, or stainless-clad rebars and dowels, with confidence in attaining a high degree of corrosion resistance, extended pavement and bridge deck life, even in heavy chloride environments, and reduced life-cycle cost. These gains are achievable without any decrease in mechanical properties, and require only the development of a PennDOT specification that permits the use of stainless or stainless-clad reinforcement.

* * * * *

I. INTRODUCTION

The expense and inconvenience associated with the repair of reinforced concrete bridge and highway structures due to reinforcement corrosion are immense. These repairs are most often required because the corrosion has compromised the integrity of the structure. Therefore, significant support exists for ideas to increase the durability of the reinforced concrete system through the prevention of the corrosion of steel reinforcing bars. One idea with growing support is to increase the corrosion resistance of the reinforcing bars by selecting stainless and stainless-clad steel as the reinforcing-bar material. Such bars can provide attractive alternatives to epoxy-coated and galvanized bar systems for numerous highway and bridge applications.

Studies to increase the durability of reinforced concrete systems for transportation structures have been and are being conducted or sponsored by numerous federal agencies and states. At the federal level, the Federal Highway Administration acknowledged, at least as early as 1982, the severity of reinforcing bar corrosion problems by sponsoring a seminar (Seminar 1982) that focussed on the problem. Later, the Office of Technology Assessment (OTA 1987) cited deterioration, through corrosion, of steel-reinforced concrete bridge decks as a “serious national problem,” and called for furthering anticorrosion methods. The National Cooperative Highway Research Program (NCHRP) has since supported several research projects in its IDEA program (TRB 1995), which addressed the issue with different approaches; and FHWA has supported major research studies of various types of anticorrosion reinforcing bars and corrosion-control methods (FHWA 1996, 2000).

At the state level, Pennsylvania and about 30 other states (and Canadian provinces) are known or reported to be evaluating stainless or stainless-clad steel as anticorrosion concrete reinforcement, either in highway applications or in laboratory research. A number of these states are funded by the FHWA Innovative Bridge Research and Construction (IBRC) Program for state projects involving corrosion-resistant reinforcing. Pennsylvania and numerous other states are also conducting trials or studies of other techniques to prevent corrosion of reinforced concrete. Figure 1 illustrates installations of stainless steel reinforcing bars in New Jersey and Ontario.

There have been several recent new reviews of the usage of corrosion-resistant rebars (Neuhart 1998, Basham 1999, Neuhart and Martin 2000). Moreover, a website (www.stainless-rebar.org) that focuses on corrosion-resistant stainless steel reinforcing is available and is regularly updated. A description of and rationale for the website has also been published (Tullmin et al 1998).

Outside of the United States, principally in Europe, numerous studies have been or are being conducted investigating similar issues. An excellent recent report from the UK (Concrete Society 1998) provides guidance on designing, specifying, and using stainless steel reinforcement. Although the report's emphasis is on European applications, the ideas presented are also applicable in the United States. Part of the report was re-published recently (Gedge 2000), and a section dealing with life-cycle costs is scheduled for presentation (Gedge and Martin 2001).

In the study reported herein, Lehigh University has examined the feasibility of using stainless steel or stainless-clad steel as corrosion-resistant concrete reinforcing material. The study was restricted to deformed and plain steel bars, including both reinforcing bars (rebars) and dowel bars. It does not include rods and wires used as pre- and post-tensioning reinforcement for precast concrete systems. The tasks in the study were:

(a) To examine the attributes of stainless steel and stainless-clad steel bars;
(b) To identify the applications significant to PennDOT where stainless steel or stainless-clad steel reinforcing has been and is being used;
(c) To review the findings of prior research studies that have been conducted on this topic;
(d) And to assess the applications, research, and material attributes, and identify the opportunities and barriers for expanding the use of stainless and stainless-clad reinforcing.

This study was conducted at Lehigh University with a grant from PennDOT through its Materials Partnership Program 96-31 administered by the Pennsylvania State University. Additional funds were provided by Lehigh through the Pennsylvania Infrastructure Technology Alliance (PITA), an alliance funded by the Pennsylvania Department of Community and Economic Development, and by the Specialty Steel Industry of North America (SSINA). The project included personnel from Lehigh's Center for Advanced Technology for Large Structural Systems (ATLSS), Lehigh's Materials Research Center, and SSINA. The ATLSS Center provided coordination. In a related, but separate, study in the same PennDOT program, Lehigh (Pamukcu 1999) is reviewing cathodic protection and electro-chloride extraction as methods of preventing the corrosion of reinforcing steel.

This final report supercedes two status reports previously submitted to PennDOT (Bower et al. 1999, 2000).

II. TYPES AND PROPERTIES OF STAINLESS STEEL

Stainless steel is defined as carbon steel containing more than 10 percent chromium by weight. The chromium serves to produce a continuous corrosion-resistant passive film. Other elements are also often added, such as nickel to produce highly corrosion-resistant austenitic stainless steel, and molybdenum to prevent pitting corrosion. In this section, the categories, salient properties, availability, and cost issues of stainless steel reinforcement are briefly examined. The corrosion resistance and life cycle cost characteristics are examined more fully in later sections.

CATEGORIES OF STAINLESS STEEL

Stainless steels have been categorized, on the basis of their metallurgical characteristics, as: austenitic stainless steels, superaustenitic stainless steels, martensitic stainless steels, ferritic stainless steels, duplex alloy steels, and precipitation hardening stainless steels (SSINA 1998, Lamb 1999). Bars in these categories have different and unequal benefits as reinforcing steel.

Stainless steels have been classified by the American Iron and Steel Institute (AISI) into general numeric types, such as Type-300 series, and have also been assigned UNS (Unified Numbering Systems) designations, such as S30400 for a Type-304 steel. In the UK and Germany, a different classification system is used. For example, the common U.S. name of Type 304 and the UNS number S30400 are replaced with the steel designation number 1.4301; similarly, Type 316 becomes 1.4401. In this report, however, the U.S. name and UNS number will be the basic nomenclature.

Austenitic Stainless Steels

Austenitic stainless steels contain 18 percent chromium and 8 percent nickel as principal alloying elements. Generally, they are classified as Type-300 series steels. If the steels also have manganese as a principal alloy, they are classified as Type-200 series steels. It is the Type-300 steels, principally Types 304, 304L, 304LN, 316, 316L, and 316LN, that have been evaluated most frequently as reinforcing steel for highway applications. Steels with the suffix L have a lower carbon content but greater corrosion resistance than their base type. The additional suffix N denotes that the steel has a higher nitrogen content to increase strength. Table 1 gives the chemical composition of these principal grades, and others, and their UNS and, where known, European designations.

The principal attribute of austenitic stainless steels is their superior resistance to corrosion. They also have excellent strength properties, and are readily weldable. An unfavorable attribute is that their coefficient of thermal expansion is relatively high.

Martensitic Stainless Steels

Martensitic stainless steels generally contain about 12 percent chromium as the principal alloying element. They also have higher carbon content than most austenitic stainless steels. They are classified as Type-400 series steels. Type 410 martensitic steel has been evaluated as reinforcing steel. Since they are hardenable by heat treating, martensitic steels can attain higher strengths than austenitic steels. They also have a lower coefficient of thermal expansion than austenitic steels. Welding practices, however, need to be more controlled. Table 1 gives the composition and UNS designation for Type 410 steel.

Table 1. Stainless Steel Grades Evaluated as Rebars.

Alloy	UNS No.	European Design-ation	Category	Nominal Chemistry									
				% Cr	% C	% Mn	% Si	% Ni	% Mo	%N	% P	% S	Other
304	S30400	1.4301	Austenitic	18.0-20.0	.08 max	2.0 max	1.0 max	8.0-10.5	--	--	.045 max	.03 max	
304L	S30403	1.4306	Austenitic	18.0-20.0	.03 max	2.0 max	1.0 max	8.0-12.0	--	--			
304LN	S30453	1.4311	Austenitic	18.0-20.0	.03 max	2.0 max	1.0 max	8.0-12.0	--	.14			
316	S31600	1.4401	Austenitic	16.0-18.0	.08 max	2.0 max	1.0 max	10.0-14.0	2.0-3.0		.045 max	.03 max	
316L	S31603	1.4404	Austenitic	16.0-18.0	.03 max	2.0 max	1.0 max	10.0-14.0	2.0-3.0	--			
316LN	S31653	1.4429	Austenitic	16.0-18.0	.03 max	2.0 max	1.0 max	10.0-14.0	2.0-3.0	.14			
Nitronic 33*	S20400	nd	Austenitic	15.0-17.0	.03	7.0-9.0	--	1.5-3.0	--	.15-.30	--	--	--
Nitronic 60*	S21800	nd	Austenitic	16.0-18.0	.10 max	7.0-9.0	3.5-4.5	8.0-9.0	--	.08-.18	--	--	--
2205	S31803	1.4462	Duplex	21.0-23.0	.03 max	2.0 max	1.0 max	4.5-6.5	2.5-3.5	.08-.20	.03 max	.02 max	
405	S40500	1.4002	Ferritic	11.5-14.5	.08 max	1.0 max	1.0 max	.5 max	--	--			Al .10-.30
410	S41000	1.4006	Martensitic	11.5-13.5	.15 max	1.0 max	1.0 max	.5 max	--	--			
430	S43000	1.4016	Ferritic	14.0-18.0	.12 max	1.0 max	1.0 max	.5 max	--	--			

*** Trade name, not an AISI Type. Nitronic is a trademark of Armco Inc.**
nd = not known by authors.

Ferritic Stainless Steels

Ferritic stainless steels are principally 17 percent chromium alloys, and are also in the Type-400 series. They differ from martensitic steels in that they are not considered hardenable by heat-treating. They are also generally less ductile, less weldable, and less corrosion resistant than Type-300 austenitic steels. Moreover, they are also magnetic. Their strength properties are equivalent to Type-300 series steels. Types 405 and 430 ferritic steels have been evaluated as reinforcing steel, and Table 1 gives the chemical composition and UNS designation for these steels.

Duplex Stainless Steel Alloys

Duplex stainless steel alloys have a combination of austenitic and ferritic microstructures and properties. Type 318 steel, also known as Alloy 2205, is an example of a duplex alloy. Alloy 2205 has been evaluated as reinforcing steel, because the duplex alloys have higher strength and greater resistance to chloride stress corrosion than many non-duplex alloys. Duplex alloys can be conventionally welded but are sensitive to welding procedures; precautions are required to avoid the development of intermetallic phases.

Precipitation Hardening Stainless Steel Alloys

These alloys are not known to have been evaluated as reinforcing steel. Although the alloys have good mechanical properties, the processing requirements have not been warranted for reinforcing applications. These alloys can be welded, but the base metal supplier should be consulted.

CORROSION RESISTANCE

Generalized corrosion of stainless steel does not occur due to a passive film that forms and is fortified by the chromium. The chromium in the stainless steel reacts with the surrounding oxygen to form a thin continuous protective layer of chromium oxide. In the event that the film is disturbed or even destroyed, the chromium oxide layer will reform in the presence of oxygen and continue to provide corrosion resistance.

Localized corrosion of stainless steel can be a concern for some conditions. The concrete/reinforcing bar/surrounding environment interfaces—isolated regions that separate their environment from the rest of the metal, and particularly those regions that are surrounded with a lower pH—are the likeliest areas for localized corrosion to occur. Also, welded joints in stainless steel can be sites for localized corrosion.

Corrosion principles, including welding issues that apply to reinforcing bars in concrete, are described in Section VI.

MECHANICAL PROPERTIES

Stainless steel can exhibit high toughness, allowing it to be handled by conventional means without serious damage. Stainless steel reinforcing bars also compare well to plain carbon steel reinforcing bars. The most common plain, or "black," carbon steel reinforcing bars (Grade 60 bars) traditionally have a minimum yield strength of 400 MPa (60 ksi) and a minimum tensile strength of 600 MPa (90 ksi). The Type 300-series austenitic stainless steels match this strength after 10 percent cold working, and duplex stainless steels match this strength easily under fully relaxed conditions. Stress-strain curves for stainless steel may not exhibit the distinct yield point that is associated with carbon steel, but yield-strength grades can be selected to be comparable. Stainless steels have ductility as much as 40 percent larger when in the annealed state, while duplex stainless steels have slightly lower ductility than carbon steel. Hardness measurements are also comparable. The moduli of elasticity for stainless steels (200 GPa [29,000 ksi]) are slightly lower than for carbon steel reinforcing bars (205 GPa [30,000 ksi]). (McGurn 1998)

Stainless-steel-reinforced concrete elements generally behave structurally very similarly to conventional carbon black-bar-reinforced concrete elements and as a result, there is usually no need for supplemental studies of the mechanical behavior of concrete elements reinforced with stainless steel.

THERMAL CHARACTERISTICS

Austenitic stainless steel has a coefficient of thermal expansion (9.5 $\mu\varepsilon/^{\circ}F$) that is nearly 50-percent higher than that for either black steel or concrete (6.7 $\mu\varepsilon/^{\circ}F$). This difference needs to be considered to ensure that, under large changes in temperature such as the occurrence of a fire, its effects are not damaging.

In this regard, it will be noted later that stainless-clad black steel bars are in use, and the differences in expansion between the cladding and the base bar have not been noted in any state trials as a concern that would cause a separation at the cladding-bar interface.

WELDABILITY

Welding austenitic stainless steel reinforcing bars poses no difficulties. The welding process is easy to perform; standard non-destructive evaluation techniques may be used to assess the welds; and if a problem is noticed using these non-destructive methods, standard weld repair methods may be used.

Fumes generated while welding stainless steel contain hexavalent chromium. These fumes are toxic, and require limited exposure levels. This condition has been studied by the National Shipbuilding Research Program's Welding Panel SP-7 (NSRP 1999, Chute and Christ 2000), but should not be a problem with the generally limited amount of reinforcing-bar welding done on a typical project.

FATIGUE RESISTANCE

Because stainless steel rebars must compete with black carbon steel bars, their fatigue resistance must also be competitive. Although the fatigue characteristics of ribbed stainless steel reinforcing bars are not known to have been studied, fatigue data are available for several grades of stainless steel used in reinforcing applications (Types 304, 304LN, 316, 316LN, 2205) (Johansson and Groth 1990, Rolled Alloys 1997, SSINA 1998). Many of the fatigue tests have been conducted in a chloride environment, since a major reason to use stainless steel is its corrosion resistance. Overall, the reinforcing bar grades have exhibited a tensile-stress-range fatigue-strength (at twenty million cycles) of 0.4 to 0.6x tensile strength when tested in air. When tested in a chloride environment with low pH, this ratio decreases somewhat. A further description of the fatigue results and chloride environment is given in Section VI.

Fatigue test data on welded joints in structural-grade stainless steel are also available (Fisher 2000) and demonstrate that the welded details in stainless steel meet the same AASHTO requirements as similar details in carbon-manganese and HSLA steels. Section VI provides further discussion.

The authors are not aware of any fatigue tests that may have been conducted to examine the fatigue resistance of stainless-clad bars.

STAINLESS CLADDING

To overcome the material cost of solid stainless steel reinforcement, stainless-steel cladding is being added to black carbon steel to produce stainless-clad steel reinforcing bars and dowel bars. Also, stainless steel tubing is being filled with grout to form another variety of dowel bar. These products and their properties are discussed in Sections III and IV.

COST

The initial cost of solid stainless steel reinforcement can be as much as six times that of conventional black bars (~$1.50/lb vs. ~$0.26/lb), adding as much as 15 percent to the total initial cost of a structure. In an environment where the major concern is initial cost, solid stainless steel reinforcement is often too expensive. Stainless-clad steel bars are about one-third the cost of solid stainless steel bars (~$0.55/lb vs. ~$1.50/lb), and thus are approximately twice as expensive as conventional black bars.

Both stainless and stainless-clad bars are being recognized, however, as legitimate, alternative reinforcement, particularly when their corrosion resistance is compared to that of black bars. Therefore, a realization is growing that the life-cycle cost of a structure may be more important than the initial project cost. Consequently, project cost and life cycle cost factors are discussed more extensively in Section VII.

III. AVAILABILITY AND PRICING OF STAINLESS AND STAINLESS-CLAD REINFORCING BARS

STAINLESS STEEL REBARS

There are six North American producers or suppliers of stainless steel rebars: Empire Specialty Steel Corporation, Dunkirk, NY 14048; Republic Engineered Steels, Canton, OH 44706; Slater Steels Corporation, Fort Wayne, IN 46801; Talley Metals Technology, Inc., Hartsville, SC 29551; Tell Steel, Long Beach, CA 90813, and Atlas Specialty Steels, Welland, ON L3B 5R7. (SSINA 1999)

For the still small U.S. market for stainless rebar, the leading domestic producer has been Empire Specialty Steel (formerly Al Tech Specialty Steel). It has supplied almost all of the Canadian and domestic requirements and has shown a willingness to quote a number of alloys, to quote small quantities, to quote from U.S. #4 to 14 bars, and to provide Cut-to-Length services and relatively short delivery times. Slater Steel of Fort Wayne has been quoting jobs, but has limited rolling capabilities with regard to the full size range. Carpenter Steel of Reading, Pennsylvania, (who recently purchased Talley Metals) has shown interest and quoted a few jobs, and has done experimental rolling of duplex 2205 alloy, but due to strong business conditions has very little melt capacity available for stainless rebars. Moreover, it judges this product to be relatively low priced compared to the normal product mix. Tell Steel in Long Beach, California, is a supplier of stainless reinforcing produced in Italy. Atlas Steel in Welland, Ontario, will also quote but in a limited size range. Figure 2 illustrates a #3 bar from Slater Steel and a #8 bar from Empire Steel.

European companies such as Acerinox in Spain and Stainless Steel Reinforcement, Ltd. in Chessington, England (Abbott 1996) are suppliers when "Buy American" provisions are not controlling in the project. Acerinox supplied the New Jersey Turnpike with some 150 tons of material for a Route 80 interchange job. It badly missed delivery, however, for a Canadian project, forcing Harris Rebar and the Ontario Ministry to acquire several hundred tons on short notice from Empire Specialty Steel to complete a project at additional cost. Acciaierie Valbruna in Italy produces a brand of stainless rebar called "Reval," which is marketed in the United States by Tell Steel.

STAINLESS-CLAD REBARS

Commercially available solid stainless-clad steel reinforcing bars are produced in the U.K. by Stelax Industries Limited under the tradename NUOVINOX. Nuovinox bars can be purchased with an austenitic cladding of 304, 304L, 316, or 316L stainless steel, or with ferritic or duplex alloy cladding. In the production process for Nuovinox bars (Stelax 1999a), low-cost carbon steel shavings (with chemical composition conforming to A615 steel) are processed into a uniform, fine granulate that is cleaned and then inserted and cold compacted in a heavy-walled stainless steel pipe. The pipe size is about 100-115 mm diameter and 6-7 mm wall thickness. The stainless pipe is produced by passing flat-coiled hot-rolled strip through a pipe-forming mill where a continuous plasma-TIG autogeneous weld is added. Compaction of the carbon steel granulate is done under pressure and results in a uniform structure and density (about 90 percent of solid steel) for the compacted material. After compaction, the composite pipes are reheated in a furnace with a reducing atmosphere, and then hot rolled, using TMCP, into clad bars at a stainless-steel rolling temperature. The bars achieve a metallurgical bond in the interface between the core and the cladding, have no voids, and have standard microstructures in the core and in the cladding. Figure 2 illustrates two pieces of a 25mm (#8) Nuovinox bar, and Figure 3 illustrates the cross-section of a Nuovinox bar and the uniform microstructure of the core.

Stelax specifies that cladding thickness on Nuovinox bars shall be a minimum of 500 µm (0.5 mil) on 90 percent of recorded thickness measurements, when cladding thickness is measured on a straight length between the bar deformations (Stelax 1999c).

Currently, the only production facility for Nuovinox bars is in Neath, Wales, in the U.K., but Stelax is seeking a manufacturing facility for the United States. There is a U.S. corporate office for Stelax in Dallas, TX 75244. Stelax aggressively markets its clad product and has orders for both trials and applications for about 3000 tons from various states for rebar and dowel bars.

REBAR PRICES

The foremost barrier to expanded highway use of stainless or stainless-clad rebars as corrosion-resistant reinforcing bars is the first cost of the bars. Approximate per pound comparative prices are given in Table 2 for straight, deformed bars of various materials.

Table 2. Approximate Reinforcing Bar Prices.

Bar Material	Price/lb.,$	Price/ft.,$ (#5 bars)	Source
Stainless, Type 304L	1.20	1.26	SSINA 02/2000
Stainless, Type 316LN	1.45	1.52	SSINA 02/2000
Stainless Clad, Nuovinox304L	0.49	0.52	Stelax 06/1999
Stainless Clad, Nuovinox316L	0.59	0.62	Stelax 06/1999
Carbon, Epoxy-coated	0.3844 (20 city avg.)	0.40	ENR, 10/23/2000
Carbon, Galvanized	0.37-0.40 (incl. delivery)	0.39-0.42	NJ Galvanizing, 03/15/00
Carbon, Black Grade 60	0.266 (20 city avg.)	0.278	ENR, 10/23/2000
(Glass) Fiber-Reinforced Polymer	30.70 (#5 bar)	0.86	Marshall Industries
(Carbon) Fiber-Reinforced Polymer	4-5x gfrp	4-5x gfrp	Composites, (09/1998 Price List)

As the table shows, the price per pound of stainless steel bars and, to a lesser extent, of stainless-clad bars is greater than that for other steel reinforcing bars that provide some degree of corrosion resistance, namely, epoxy-coated bars and galvanized bars. Fiber-reinforced polymer (FRP) bars are, by far, the most expensive corrosion-resistant bars based on price per pound. When the basis is shifted to price per foot, however, straight glass FRP bars have a material cost between that of stainless clad bars and stainless bars. A major factor contributing to the price of stainless steel bars is the price of raw materials. Nickel, chromium, and molybdenum used in these bars are mined mostly in parts of Africa and Australia and, therefore, are dependent on international politics, monetary policies, and production decisions. To offset changes in raw materials prices, which can fluctuate widely, stainless rebar producers may place a variable surcharge on stainless bars.

As a consequence of the price comparison, the producers, suppliers, and trade associations promoting stainless/stainless-clad bars have focused on other significant cost aspects: the effect of the bars on project cost and on life-cycle cost, as discussed in Section VII.

STAINLESS AND STAINLESS-CLAD DOWEL BARS

Dowel bars are reinforcement used to transfer shear force across the joints of adjacent highway slabs and to maintain equal elevation of these slabs. Ranging in length from 1 to 2 feet, they are usually smooth bars with about 1 ½-inch diameter. Because the dowel bars are at the joints of highway slabs, they are exposed to moisture and de-icing salts. If they corrode, they cause distress at the joint, as shown in Figure 4a.

Dowel bars may be solid bars or tubular matrix-filled bars. As solid bars, they may also be clad bars such as stainless-clad bars. As tubular bars, they may be either pipe or tubing and, as tubing, either seamless or welded. Stainless steel tubing is a frequent dowel bar material. Figure 4b illustrates the cross-section of a grout-filled stainless tubular dowel.

Solid stainless steel dowel bars are supplied by the same suppliers as stainless steel rebars. Additionally, being generally smooth bars, they can be obtained from the larger group of stainless steel bar suppliers. Plain stainless-clad Nuovinox dowel bars are available from Stelax.

Commercially available grout-filled stainless-tubing dowel bars are produced in the United States and Canada. Generally, the tubing is ERW (electric resistance welded) tubing produced from stainless steel strip and then filled with grout or mortar. One U.S. producer is Damascus-Bishop Tube Co. [Greenville, PA (724-646-1500)], a unit of the Italian firm Gruppo Marcegaglia. Matrix fillings of both grout (e.g. Master Builder 928) and of hydraulic cement have been used. When tubular dowel bars are used, the common practice is to use internal plastic end caps to stiffen them and protect the inside diameter prior to injecting the matrix filling.

Currently, dowel bars have an installed cost of about $2.50 per bar, according to Illinois engineers. Minnesota Department of Transportation engineers have reported a cost of $5.00 to $10.00 per bar might be acceptable in some installations where the corrosion-resistant benefits of stainless steel dowel bars could be maximized. In this regard, SSINA (Neuhart 2000) has transmitted representative costs to Minnesota for 18-inch-long dowel tubing of 304L or 316L, various wall thicknesses, and various ODs. The cost per dowel tube ranges from $5.40 to $9.00

depending on the variables. Grout filling adds to these costs. Basketing costs are not included because they would apply with black dowels too.

ACCESSORIES AND SPECIAL NEEDS

Placing reinforcement generally involves using a number of accessories in conjunction with the reinforcement, including chairs, ties, and mechanical splices. Special tools to simplify affixing these accessories are also often required. Further, special needs generally exist involving bending bars and adjusting their lengths. Finally, tools are often needed for finding rebars in concrete decks and walls.

Accessories are not a barrier for stainless and stainless-clad bars, except with regard to mechanical splices. Stainless steel chairs and tie wires are readily available. In fact, stainless ties are often specified even with non-stainless reinforcement. Moreover, automatic rebar tying tools that accommodate stainless tie wire are available from different suppliers [the E-Z Grip U-Tier machine from Southhold International in South Bend, Indiana (888-746-0050); and the RB 392 machine from Max USA Corporation in Garden City, New York (800-223-4293)]. Bar splices in stainless steel are not currently widely available as standard products. Headed Reinforcement Corp. in Fountain Valley, California (714-557-1455) supplies stainless splices for bars that have upset ends. Three other major suppliers of splicing systems in the United States; Barsplice Products in Beavercreek, Ohio (937-427-6466), Erico in Solon, Ohio (800-248-2677) and Splice Sleeve North America in Ontario, Canada (909-937-7161) have indicated that they would produce stainless steel splices if a market for them develops. In this regard, Barsplice currently has a research program working with material supplied by Empire Steel. It has made couplers for No. 4 and No. 6 bars, and is completing a coupler for No. 5 bars. The bars and couplers are to be tested at the University of Dayton in the latter half of 2000. Erico has supplied stainless couplers to jobs in Ontario and Michigan. It will continue to do this on an as-ordered basis but does not have current plans to establish a product line. Stainless steel splices are essential with stainless and stainless-clad reinforcing to prevent galvanic corrosion at splice locations. With stainless-clad bars, the splice must also be selected so as not to penetrate the cladding during installation.

Threaded bar splices are not candidates, therefore, with clad bars; rather, wedge-type and bolted splices must be used.

Additionally, most reinforcement installations include some bent bars, and the bending operation often introduces special requirements to ensure that reinforcement that gains corrosion resistance through cladding or coatings maintains its corrosion resistance. (One example is the need to pre-bend black bars before applying an epoxy coating.) Stainless steel bars may be readily bent to the same 180° bend diameters as uncoated carbon steel bars. However, the pins around which the rebars are bent should preferably also be stainless steel, and not ferritic steel, so as not to impart dissimilar metal particles on the stainless bars and provide corrosion initiation sites. As shown in Table 3, the required pin diameter for bending the stainless-clad Nuovinox bars is considerably larger than for solid steel bars. (The bend pins must be non-ferritic steel, just as with solid bars.) These larger-diameter bend requirements could represent a barrier to using Nuovinox bars in some applications. However, this barrier also affects galvanized steel rebars and pre-coated epoxy-coated bars.

When the supplied length of reinforcing bars needs to be either extended or reduced, which requires either welding bars or cutting them at the construction site, further special requirements apply to ensure that the reinforcement maintains its corrosion resistance. Stainless steel rebars can be readily cut in the field and can be readily welded with the proper non-ferritic stainless steel weld metal. However, the contractor must ensure that the field welder has the proper weld metal and is experienced in welding stainless steel. Stainless-clad Nuovinox bars can also be both cut and welded in the field. When welding is required, these bars, like solid stainless bars, must be welded with non-ferritic stainless steel weld metal. Exposed cut ends are a condition that needs attention, however, with Nuovinox bars, in order to eliminate the exposed carbon-steel core and prevent corrosion. Stelax offers three alternatives to its customers: (1) Weld the cut ends with stainless steel weld metal; (2) Use compatible-grade stainless-steel end caps, which are pre-filled with a suitable adhesive and then press fit to the rebar allowing the adhesive to extrude up the rebar to prevent moisture reaching the cut end; and (3) Seal the cut ends with epoxy, just as is done with the cut ends of epoxy-coated rebars. These alternatives are quite similar to the alternatives required with the cut ends of epoxy-coated and galvanized rebars. In each case, they increase installation cost of the bars.

With regard to locating rebars in existing concrete decks and walls, the use of stainless or stainless-clad bars should not pose problems. Companies, such as Zircon Corporation in Campbell, California (408-866-8600), market metal locators capable with both magnetic and non-magnetic bars.

IDENTIFICATION OF STAINLESS BARS

Stainless steel rebars may introduce handling and identification concerns in locations where both carbon and stainless steel materials, or mixed stainless steel materials are being used. Identification is necessary for proper placement, but is also necessary in other processes such as welding. In this regard, Empire Specialty Steel reportedly has new rolls that imprint their mill identification (EMP) but do not imprint grade and bar size onto rebars. ASTM A955 provides for source, size, and grade imprints, but generally it has been taken exception to, as the market had not selected what alloys were standard in the stainless rebar field. As this becomes clearer, new editions of ASTM A955 may address this more specifically. Figure 5 shows, however, that stainless steel bars, because of their bright appearance, should be readily separable from black, carbon steel bars and epoxy-coated bars.

IV. STANDARDS FOR STAINLESS REINFORCING

ASTM SPECIFICATIONS

Stainless Steel

Stainless steel bars for concrete reinforcement are covered by ASTM Designation A955M-96, "Standard Specification for Deformed and Plain Stainless Steel Bars for Concrete Reinforcement [Metric]." Deformed bars are commonly called "rebars" and plain bars are often used as dowel bars. There are requirements for chemical composition, deformation geometry, mechanical properties, bend tests, and corrosion resistance. A supplemental requirement for magnetic properties may also be invoked.

The specification recognizes three grades of bars: Grade 300 (minimum yield strength of 300 MPa at 0.35 percent strain), Grade 420, and Grade 520 (42.8, 60.0, and 74.3 ksi, respectively). Included bar diameters range from No. 10 (9.5 mm) to No. 57 (57.3 mm), corresponding to #3 to #18 bars in in.-lb. units. A955M-96 allows the same bar grades and bar designations with the same mass, dimensional, and deformation requirements as ASTM Specification A615/A615M-96a for billet-steel bars (see note below). Moreover, the bend-test requirements are the same in A955M and A615/A615M. However, in A615/A615M, yield strength is determined at a strain of 0.5 percent of gage length for Grades 300 and 420 and at 0.35 percent for Grade 520, whereas a strain of 0.35 percent is used to determine yield strength for all stainless steel grades in A955M. A955M, therefore, has the more stringent requirement with lower strength grades because it relies less on strain hardening to upwardly influence the measurement of the yield strength. A955M also allows corrosion-resistance requirements depending on whether the stainless steel bars are to be austenitic (e.g., Types 304 or 316) as opposed to ferritic (e.g., Types 405 or 430), martensitic (e.g., Type 410), or a duplex alloy (e.g., Type 318), as well as on magnetic-permeability requirements.

While A955M does not directly include a composition requirement, the selection of a specific grade of stainless, such as 316L, by the user serves as a chemical composition requirement. Moreover, with this composition control, there is a high degree of quality assurance on the mechanical properties and on the fracture toughness of the reinforcing.

A revision of A955M has been drafted and is in committee review, with the salient subcommittee (A1.05) scheduled to meet in Orlando in November 2000.

Note: ASTM A616/A616M-96a for rail-steel reinforcing bars and ASTM A617/A617M-96a for axle-steel reinforcing bars have bar grades, bar designations, and other properties that are more limited than those for A615 bars. Hence, they are not included in the comparison between A955 stainless bars and A615 bars.

Stainless-Clad Steel

There is no ASTM specification for the stainless-clad Nuovinox bars produced by Stelax, however, and this will be an impediment to their use if not remedied. Stelax has developed, and submitted to both ASTM and AASHTO, a proposed specification for its bars (Stelax 1999b). Identified by Stelax as STLX 995-99, "Standard Specification for Deformed and Plain Stainless-Steel Clad Carbon Steel bars for Concrete Reinforcement [Metric]," it follows A955M in style, format, and content. An ASTM Subcommittee (chaired by Professor M. Sellars of Sheffield University) has been formed to review STLX 995, and recently met on May 22, 2000. A revised specification is likely when the Subcommittee completes its work. At present, however, there are some important, critical differences between A955M and STLX995:

- While Stelax would allow welding its bars, it carefully cautions that the welding procedure should be suitable for both the stainless cladding and the carbon-steel core.
- Stelax prefers welding to be conducted with stainless weld metal on cut ends of the bars to maintain corrosion resistance.
- If structural welds are to be made and are specified in the order to Stelax, Stelax may tailor the composition of the carbon steel core to facilitate welding.

- Stelax does not have provisions for bars larger in diameter than bar designation 43 (US No. 14 bar), whereas both A955M and A615/615M have provisions for bars up to bar designation 57 (No. 18 bar).
- Pin diameters for 180-degree bends are larger for Stelax clad bars than for uncoated solid bars (A955M and A615/A615M). This requirement is to prevent bend cracking in either the stainless cladding or carbon-steel core, and represents a less severe requirement than for solid bars. On the other hand, the Stelax bend requirements are at least as severe as the requirements for A775/A775M epoxy-coated bars. The following table compares the bend-test requirements.

Table 3. Mandrel Diameter for 180° Bend.

Bar Designation No.	STLX 995-99 all grades	A955M and A615/615M			A775M (after coating)
		Gr. 300	Gr. 420	Gr. 520	
10	75	35	35	--	100
13	100	45.5	45.5	--	--
16	125	54	54	--	125
19	150	95	95	95	150
22	175	--	110	110	--
25	200	--	125	125	200
29	230	--	203	203	230
32	250	--	224	224	--
36	280	--	252	252	280
43	not covered	--	387 (90° only)	387(90°only)	430(90°only)
57	not covered	--	513 (90° only)	512(90°only)	580(90°only)

Based on a comparison of the deformation requirements (Table 1 in both STLX 995-99 and ASTM A955M-96), the deformations on Stelax stainless-clad bars would seemingly be similar to those on solid stainless bars produced in the United States. However, there have reportedly been significant geometric differences that led to the differences in bend requirements (Powers 2000). The Stelax deformations were strongly trapezoidal in cross-section while U.S. rebar deformations were far more rounded, thus providing less strain concentrations. Reportedly, after March 2000, Stelax began changing its roll design to achieve a deformation profile closer to that achieved in the United States.

There are also other differences between STLX 995 and ASTM A955M (e.g., STLX 995-99 deletes reference to magnetic permeability), but these are probably of less significance than those just discussed.

AASHTO SPECIFICATIONS

AASHTO's *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, through the 2000 Edition, do not yet include a specification for either stainless or stainless-clad reinforcing bars. The AASHTO Standards only include M31 (ASTM A615), M42 (A616), and M53 (A617), or their metric equivalents. Hot-finished stainless bars conforming to ASTM A276 are approved by AASHTO, and AASHTO states that "(other) stainless steel....may be used provided that it conforms to the...requirements of...other published specifications that establish its properties and suitability...." (LRFD Bridge Design Specification, Section 6.4.7). Thus, while specific reference to ASTM A955 is absent in AASHTO, and this absence is a barrier to their use, stainless bars might be used under the latter condition of Section 6.4.7.

AWS WELDING CODE

Section 1.3, Reinforcing Steel Base Metal, of the ANSI/AWS Standard D1.4-98 (AWS 1998) Structural Welding Code for Reinforcing Steel does not explicitly include stainless steel bars conforming to ASTM A995. However, Section 1.3.2 allows such bars when they are approved by the applicable general building code or by the engineer. Further, Section 1.4, Welding Processes, specifically allows rebar welding by the SMAW, GMAW, and FCAW methods, which are acceptable methods with stainless bars.

Filler metal requirements for stainless steel are not specified in D1.4-98, but the Standard allows filler metal selection to be subject to approval by the engineer. Their selection is important not only to make the welds crack-free, but also to sustain high corrosion resistance because welding of stainless steel may result in some loss of corrosion resistance in the weld and the weld heat-affected-zone (HAZ). One reason is a tendency for chromium carbides to form in the HAZ, which results in a chromium-depleted area and impedes the formation of the passive corrosion-resisting film. This process is called sensitization. Another reason is that micro-segregation occurs as the weld metal cools. Molybdenum (Mo), especially, tends to segregate during solidification. Since Mo adds resistance to pitting corrosion, the segregation leads to areas of reduced pitting resistance. Filler metals with stabilizing elements (to compensate for sensitization) and with higher Mo content than the base metal (to compensate for segregation) reduce the above effects and are readily available for the commonly used grades of stainless steel rebars.

A brief table of standard stainless steel filler metal alloys follows. The applicable specifications are AWS A5.4 and ASTM A298.

Alloy	**UNS No.**	**Filler Metal Alloy**
304	S30400	E308
304L	S30403	E308L, E347 (S34700)
316	S31600	E310
316L	S31603	E316L, E316Cb
2205	S31803	E2209, ER2209

Welding of stainless steel may produce fumes of hexavalent chromium, which are toxic and require limited exposure levels. Although this may be of minimal concern when welding is performed on an open site, the toxicity levels must be considered.

PENNDOT SPECIFICATIONS

The PennDOT specifications (1996) also do not recognize stainless or stainless-clad reinforcing bars. Section 709.1 – Reinforcement Bars is limited to black steel bars meeting ASTM A615M (AASHTO M31M), A616M (AASHTO M42M), or A617M (AASHTO M53M) or to epoxy-coated steel bars meeting ASTM D3963M (AASHTO M284M). Because PennDOT may be guided by the AASHTO Specifications, it is possible that PennDOT's adoption of specifications for stainless and stainless-clad reinforcing bars will follow their adoption by AASHTO.

OTHER STATE SPECIFICATIONS

Because numerous states are evaluating stainless and stainless-clad reinforcing bars, some agencies within these states have developed project-specific specifications. For example, for the (New Jersey) Garden State Parkway-Contract No. 123-996, Section 523 of the contract allows "High Performance Reinforcement – HPR (stainless steel reinforcement)." Section 523.02 cites ASTM A955M as the reference specification. However, it adds exceptions that limit the choice of stainless steel to two grades – 316LN and Duplex 2205 – and tighten tensile properties and imposes additional requirements (mandating descaled bars, allowing only one grade (316L) of appurtenances such as ties and chairs, and requiring isolation from other metallic objects). Similarly, Michigan DOT has issued a "Special Provision for Reinforcement, Stainless Steel." It allows four types of stainless steel (304, 316, 316LN, and 2205) and requires them to be metric grade meeting ASTM A955M (Michigan 1999). If the bar chairs, wire ties, and tie-down wires are stainless, they must be Type 316 steel. The provision also specifies that no contact must exist between stainless reinforcement and either coated or uncoated carbon steel reinforcement. Thus, the absence of a prevailing AASHTO specification for stainless rebars is overcome by appropriate engineering judgment and decisions embodied in individual DOT specifications.

ONTARIO PROVINCE STANDARD

The Canadian Standard Association Standards (CAN/CSA) has a specification G30.18-M92, "Billet Steel Bars for Concrete Reinforcement," which allows stainless steel reinforcing. To further the use of these bars, however, Ontario Province Ministry of Transportation issued an amendment to OPSS 905 (Ontario Province Special Standard) and OPSS 1440 that added specific language approving the use of deformed stainless steel rebars in highway bridges and other applications (Pianca 2000a). Amended OPSS Section 905.02 now references CAN/CSA G30.18-M92 and ASTM A955M-96. Moreover, Section 905.03 redefined "reinforcing steel bars" to mean "deformed steel bars or deformed stainless steel bars used for the reinforcement of concrete." Section 905.05.01 allows the austenitic stainless grade 316 LN and the duplex ferrite-austenite alloy 2205. OPSS Section 1440.05.13 specifies that the bars conform to minimum Grade 420. Section 905.05.04.03 specifies that mechanical connectors and splice bars also be one of the above two grades of stainless steel. OPSS 905.07.02.06 also specifically disallows welding of reinforcing stainless steel bars (except for stainless spirals) and 905.07.02.02.1 directs that stainless bars be electrically isolated from non-stainless steel, either through distance (20 mm minimum) or through the use of neoprene sleeves. Ontario's provision against welding is based, in part, on lack of a need to weld (they have a Canadian supplier for stainless steel couplers) and, in part, on a concern about reduced corrosion resistance for welded stainless rebars (Pianca 2000 b). This latter topic is discussed in Section VI.

Stainless-clad reinforcing bars are not recognized in OPSS 905, but the Ontario Ministry of Transportation is conducting studies on commercially produced Stelax Nuovinox bars.

BRITISH STANDARD SPECIFICATION BS 6744

Deformed and plain stainless steel concrete reinforcing bars are covered by the British Standard Specification BS 6744:1986 (BSI 1986). The specification, "Austenitic Stainless Steel Bars for the Reinforcement of Concrete," was issued for solid stainless steel bars in 1986. It has requirements for chemical composition, deformation geometry, mechanical properties, and corrosion resistance. Bar diameters can range from No. 6 (6-mm diameter) to No. 40 (40-mm diameter). The requirements restrict the bars to either of two austenitic types of stainless steel, Types 304 and 316, and to one strength grade of deformed bar (Grade 460) and one strength grade of plain bar (Grade 250). (Grade 460 has a minimum yield strength of 460 MPa (65.7 ksi) at 0.43 percent strain, and Grade 250 has a minimum yield strength of 250 MPa (35.7 ksi) at 0.33 percent strain.)

Although BS 6744 has existed as a material specification since 1986 for countries that have adopted British Standards, stainless steel rebars have not been covered explicitly in design codes, at least through 1998 (Concrete Society 1998). Nevertheless, BS 6744 is currently being reviewed and is expected to be updated (Concrete Society 1998, Milne 2000). In the update, higher-strength grades and a broader range of steel grades are anticipated.

For stainless-clad reinforcing bars, there currently is no BSI specification equivalent to BS 6744.

EUROPEAN STANDARDS

Eurocodes (other than BS 6744) do not yet specifically address the use of stainless steel rebar in bridges or highway structures.

However, it has been reported that a few grades of stainless steel reinforcing bars have been specified for projects in France (types 1.4307 and 1.4404 [304L and 316L]), Germany (type 1.4571), Norway and Finland (types 1.4301, 1.4401, 1.4436), and Italy (types 1.4301 and 1.4401) (Concrete Society 1998). The product literature (REVAL 199x) for bars produced in Italy by Acciaierie Valbruna indicates that the Valbruna bars will meet "any national standard in Europe," including "prENV 10080, the European Standard intended to cover stainless steel reinforcement bars in Europe." The Valbruna bars also will "comply to Eurocode 8 class DC'M'" (an intermediate ductility class suitable for earthquake environments). The codes mentioned are not end user specifications for stainless steel rebar applications, but relate to the steel itself.

It is expected that the revised BS 6744 will become the European standard.

PACIFIC RIM STANDARDS

Little is known by the authors about standards for stainless and stainless-clad reinforcing in Pacific Rim countries. One report (Concrete Society 1998) indicates that American codes are used. Also, one contact with Pohang Steel and Iron in Seoul, Korea, reported that currently there is no Korean Standard covering stainless reinforcing. However, experimental use of stainless rebars is reportedly included in the Yong-Jong Grand Bridge, a major thoroughfare connecting Seoul to the International airport.

V. IN-SERVICE TRIALS AND PERFORMANCE OF STAINLESS AND STAINLESS-CLAD REINFORCING STEEL

The number of highway projects where stainless and stainless-clad reinforcing bars have been or are being installed, particularly in the United States, will increase markedly over the next few years if the current highway applications and trials are successful. The federal government has allocated significant sums of money in TEA 21 for both research and construction use of innovative building materials, as part of an effort to upgrade the nation's infrastructure. These funds should encourage states to use more expensive, but higher quality and more corrosion-resistant systems like stainless steel reinforcing bars to reduce the life-cycle cost of a highway project.

As stainless and stainless-clad reinforcing bars are relatively new products, there is a limited amount of data of a long-range nature. However, the following examples describe how and where stainless or stainless-clad reinforcement has been or is being installed or evaluated, and the results known to date. Among states, Pennsylvania is listed first, followed by other states in alphabetical order. Then, other North American and overseas examples are described. Other reviews of stainless steel reinforcement applications (Neuhart 1998, Stelax 1999a) and direct e-mail contacts with states provided the basis for these examples. Although these examples show broad usage, new projects are initiating regularly, and this review may have overlooked them. Also, a vast number of laboratory evaluations of the corrosion resistance of stainless reinforcing have been conducted, which are summarized in Section VI.

PENNSYLVANIA

In 1975, the Pennsylvania Department of Transportation (PennDOT) placed stainless-clad steel reinforcing bars in the northernmost span of a bridge deck on State Route 309 in Luzerne County. Specific examinations of the reinforcing bars have not occurred recently, because the bridge inspections have not disclosed unacceptable distress. The cladding technique used for the installed bars was an experimental process conducted by Bethlehem Steel Corporation using Type 316 stainless steel, and is not indicative of current rebar cladding technology.

PennDOT reportedly has also conducted a limited laboratory evaluation test in which four cut lengths of 1 ½-inch-diameter, plain (no deformations) Stelax bars were placed in an environmental (salt) chamber for 600 hr at 200F. Three bar lengths had no protection on the cut ends and corroded badly. The fourth had an epoxy coating on the cut ends; at one end the coating successfully prevented corrosion, at the other end the coating had run out the sides of the bar and some corrosion occurred under this part of the coating.

CONNECTICUT

Connecticut has received an FHWA Innovative Bridge Research & Construction (IBRC) grant to apply stainless steel rebars in the deck of a new bridge, the Church St. South Extension Bridge, in New Haven. (Rubeiz 2000 is the reference for this and some later IBRC award information.)

DELAWARE

Delaware was allocated $220K from the IBRC Program to install stainless-clad Nuovinox rebars in a SR 82 bridge over Red Clay Creek

FLORIDA

The Florida Department of Transportation and the University of South Florida initiated a two-year project sponsored by Stelax Industries, Ltd. (Powers 1999). This project is focusing on the long-term performance of Nuovinox stainless-clad steel bars in salt-contaminated concrete. A bridge (SR 679 over Burnces Pass) will be constructed using the Stelax product and $128K from IBRC. Florida has considered solid stainless steel reinforcing bars in the past, but deemed them cost prohibitive. As stainless-clad steel bars are priced similarly to epoxy-coated reinforcing bars, and because the use of epoxy-coated bars is not permitted in the State of Florida, the Nuovinox bar is being viewed as a means of cost effective corrosion control. However, as indicated earlier on p. 21, Florida DOT has expressed concerns to Stelax about the deformation geometry on the Nuovinox bars.

ILLINOIS

The Illinois Department of Transportation (IL DOT) has conducted yield strength, tensile strength, and percent elongation tests on both stainless-clad steel reinforcing bars and stainless-clad steel dowel bars (Gawedzinski 1999). The provider of the stainless-clad steel products was Stelax.

The use of Stelax's Nuovinox stainless-clad steel dowel bars came from a study of alternative materials for dowel bars. The study started with fiber composite dowel bars and was then expanded to fiber composite tubes filled with grout and stainless steel tubes with grout. Later, at the request of the FHWA, Illinois looked at stainless-clad steel dowels, using Type 316 and Duplex 2205 stainless steel dowels for comparison.

The 1-1/2 inch diameter stainless-clad dowel bars were tested and compared to AASHTO Specification M227. The bars were recorded as having an average yield strength around 100,000 psi, an average tensile strength around 113,000 psi, and an average percent elongation around 4 percent. The strength values well exceeded the AASHTO minimum requirements for stainless steel dowel bars, prescribed as being 39,000 psi and 70,000 psi respectively. The percent elongation, however, was well below minimum specifications, listed as being 14 percent. With these results, IL DOT has embarked on a field trial using stainless-clad steel dowels. Pavement test sections were installed in May 1999 and are being evaluated semi-annually for five years. This evaluation will examine results from the use of a falling-weight deflectometer.

With the stainless-clad steel reinforcing bars, bend test results were inconsistent in the first two batches of product examined. The first batch experienced longitudinal and transverse cracks in the cladding in bend tests required for AASHTO M31 bars. The second batch of clad bars passed the bend tests while exhibiting similar strengths. One possible explanation given for the cracking in the first batch is that those bars were stretched as they were pulled through the roller mill causing a stretching of the cladding. However, due to the inconsistency in the batches, ILDOT is testing a third sample batch of stainless-clad steel reinforcing bars to validate the behavior of the second batch.

INDIANA

The state of Indiana will be using stainless-clad steel reinforcing in a rehabilitation project of a bridge on I-65. IBRC is providing $85,000. As it is the first time they are using stainless-clad steel bars, handling measures will be similar to those used for epoxy-coated reinforcing bars. Handling machines will be equipped with padded contact areas to ensure that the bars are installed in the same condition that they were received. The amount of bridge life to be gained from this rehabilitation is estimated as being at least 30 years. It was reported that the primary reason provided for Indiana's usage of the stainless-clad steel reinforcing bars was "aggressive" marketing of the product by Stelax Industries, Ltd. It is projected that an evaluation and recommendation of further use or discontinuance will only occur some years from now (Snyder 1999).

IOWA

As part of an FHWA demonstration project, the Iowa DOT initiated a 5-year study of the highway application of solid stainless steel and fiber-reinforced-polymer (FRP) dowels, beginning in 1997 (Cable and McDaniel 1998). The intent was to minimize joint faults, spalling, and cracking that begins with dowel corrosion. The highway work followed several years of laboratory testing on similar dowels at Iowa State University. The 2,430-foot-long highway test site is located in Des Moines as part of the US 65 bypass, and consists of four sections; two for FRP dowels, one for stainless steel dowels, and one for standard epoxy-coated dowels. The steel dowels are 1 ½ inch in diameter; the FRP dowels are 1 7/8 inch in diameter. Dowel spacings are 8 and 12 inches. The 1998 report indicates that the stainless dowels (the steel grade is not identified) tended to undesirably bond to the concrete and prevent movement and obstruct load transfer unless greased. It also reports that placing the stainless dowels was more difficult than placing FRP dowels because the steel basket with the stainless dowels tended to sway and collapse. Deflection testing, drop testing, and joint faulting will be monitored twice a year during the project.

LOUISIANA

In Louisiana, 340 tons of Nuovinox stainless-clad steel reinforcing bar are to be used in all cast-in-place concrete on a railroad overpass bridge on US 71 in Bossier Parish (Stelax 1999a).

MARYLAND

The Maryland State Highway Administration installed stainless steel dowel bars in the joints of a short section of reinforced concrete pavement on I-97 South. The remainder of the joints used Maryland's standard epoxy-coated dowels. No difference was observed between the initial performances of the two different dowels (Weisner 1999).

MAINE

The Maine Department of Transportation is conducting tests on Grade 420 Nuovinox stainless-clad steel reinforcing bars in their central laboratory in Bangor (McGinnis 1999). The bars are No. 20 (U.S. #6) made by Stelax. Yield strength was measured as 484 MPa (70.2 ksi), tensile strength as 787 MPa (114.1 ksi), and elongation as 11 percent over 200 mm. These values were all above specified minimums. Additionally, bend tests resulted in neither cracking on the outside radius nor wrinkling on the inside radius. Weight and deformation requirements were also satisfied.

As a result, all reinforcing steel used in the construction of the concrete roadway, sidewalk, slab, and concrete transition barriers of the Fort Kent Mills Bridge during 1999-2000 will be made of Nuovinox bars. Additionally, construction on the Mopang Bridge on Route 9 in Devereaux has been divided into two sections, one of which will be reinforced with Nuovinox stainless-clad steel reinforcing bars, while the other will be reinforced with epoxy-coated reinforcing bars (McGinnis 1999).

The main objective of these projects is to evaluate the cost effectiveness of the Nuovinox stainless-clad steel reinforcing bars. The Maine Department of Transportation has determined that the cost of using solid stainless steel bars is prohibitive for highway construction. However, the department feels that the lower cost of stainless-clad steel makes it an alternative worth investigating. Secondary objectives of the project include determining the performance of the product in relation to availability, fabrication, ease of handling, repair, and service. The reasons provided for having two site evaluations are several. First, two different contractors and two different engineers will construct the projects. This allows for the possibility of different encounters between individuals and the product. Additionally, the two bridge locations have different traffic patterns and different climate conditions, with one a more coastal environment with higher expected chloride rates (McGinnis 1999).

One corrosion-research variable at the Fort Kent Mills Bridge is that end caps are being attached to most ends of the Nuovinox bars but a few ends of these bars will intentionally be placed without end caps.

MICHIGAN

Type 304 stainless steel reinforcing bars (33 tons) were used in 1985 in an I-696 bridge deck near Detroit (over Lenox Road near I-75). The bars were 16 mm in diameter (#5 bars). Bethlehem Steel produced the stainless steel reinforcing bars, which were supplied by Joslyn Steel (now Slater Steel, Fort Wayne, Indiana). Although the Michigan Department of Transportation (MDOT) had not had problems with epoxy-coated reinforcing bars, they chose stainless bars for the deck to ensure that they had a solid back up system for corrosion resistant bars. Additionally, the stainless steel bars were viewed as an insurance policy for future projects where rehabilitation will be difficult.

Two cores were removed for inspection in 1993, as part of a Wiss Janney Elstner study (WJE 1993). The cores had a measured water-cement ratio of 0.50, with a cement content of 335 kg/m^3 (20.9 lb/ft^3). The compressive strength of one core was 35 MPa (5,075 psi); hence, the concrete was judged to be of good quality. The chloride levels observed in the concrete were already at the threshold for typical black bar. Reinforcing bars were located at different levels in the cores and differing chloride concentrations were present at those different depths. Moreover, the two cores had cracks that intersected the reinforcing. But despite the different concentrations, the stainless steel reinforcing bars appeared to be unaffected and no significant corrosion was observed. It was concluded that the cracks in the cores were caused by thermal shrinkage effects alone, and not by corrosion (Beck 1999, McDonald et al 1996, Stainless Bulletin 1999). An evaluation via corings and visual inspection of the deck has continued to be done at periodic intervals. The 304 reinforcement has shown no signs of corrosion, and the deck remains in good physical condition.

A project scheduled for Year 2000 will involve the use of stainless steel for a deck replacement. The geometry of the bridge (on the Davison Expressway) is forcing MDOT to use a thinner slab than its standard, and by using stainless steel reinforcing bars, it hopes to reduce the concrete cover and get the same effective deck section. For other future construction projects, an empirical bridge design is being considered to reduce the amount of steel required, thereby partially offsetting the higher cost of using stainless steel. Overall, MDOT optimistically anticipates an "infinite" life from stainless steel reinforcing bars, with a structure's life span being determined by general degradation and obsolescence (Beck 1999).

Stainless-clad steel reinforcing bars are also beginning to be evaluated by MDOT due to their lower initial cost, compared to solid stainless bars. A future demonstration project using stainless-clad steel is a possibility for Michigan, but further research has been determined to be necessary first (Kahl 1999).

MINNESOTA

Minnesota received $30K from IBRC for a new bridge, TH 100 under 36th Ave in Crystal, for installing stainless-clad steel reinforcing bars in a High Performance Concrete Pavement (HPCP) Research Project where construction began in the fall of 1999. Stelax is supplying the stainless-clad steel reinforcing bars (Rettner 1999).

The goal of the HPCP project is to make road structures maintenance free for 60+ years. Indications in Minnesota are that epoxy coated bars are not lasting beyond a 30- to 35-year design life without significant corrosion. The selection of stainless-clad steel over solid stainless steel was a decision based on cost, but the benefits weighted against the total costs (as the stainless-clad steel bars are only one expense in the HPCP Project) still need to be calculated. How many road structures need a design life of 60+ years is a question with which Minnesota is wrestling (Rettner 1999).

Minnesota had also planned to install 60,000 Nuovinox dowel bars in highway expansion joints along I-35W, leading to the Mall of America, just south of Minneapolis (Stelax 1999a). However, Minnesota reportedly cancelled this application due to an unacceptable surface quality of these dowels.

MISSOURI

Missouri received $185, 000 from IBRC to use solid stainless steel rebars in replacing a Rt. 6 bridge in Galt. In their documents, Missouri allowed three stainless alloys to be bid: 316LN, 2205, and Nitronic 50. The bars had to meet A955M Grade 420, and were supplied by Empire Steel. Bar diameters included 13 mm, 16 mm, and 19 mm (#4, 5, and 6). No adjustment in concrete design is being made.

Missouri has also submitted an IBRC 2001 project to use stainless-clad rebars in a bridge (Purvis 2000).

MONTANA

Montana received an IBRC grant to install stainless steel rebars in the concrete deck of a replacement bridge on US Rt. 2. Montana plans to use 316LN bars, with 2205 bars as an alternative. The bars will be 13, 16, 19, and 22 mm (#4, 5, 6, and 7). Empire Steel and Slater Steel are expected to be the primary suppliers, with Talley Metals possibly supplying any 2205 bars. Lap and mechanical splices are planned, but not welded splices. No adjustment in concrete design is being made. (Mends 2000)

NEW JERSEY

In 1985, carbon steel reinforcing bars with an external cladding of Type 304 stainless steel were used as reinforcement in an I-295 bridge deck near Trenton (over Arena Drive in Hamilton Township). This bridge is heavily traveled and was built with steel girders and stay-in-place metal decking, with a cast-in-place 240mm- (9.5 in) thick reinforced concrete bridge deck. The deck was overlaid with 25-37 mm- (1-1.5 in) thick concrete overlay using latex-modified concrete. In a study reported in 1995, four cores were removed for inspection, two from delaminated overlay areas without cracks and two from delaminated overlay areas containing cracks. The four cores contained 9 stainless-clad steel bars, with the concrete cover ranging from 50 to 62 mm (2 to 2.5 in) and averaging 60 mm (2.4 in). The bars were in excellent condition, with one exception. Under the end cap of this bar, the exposed black steel at the cut end had corroded. The measured chloride levels were below the threshold value for black steel in concrete, causing the experimenters to hypothesize that a local low pH environment existed under the protective end cap that prevented passivation of the steel from occurring and caused subsequent corrosion (Stainless Bulletin 1999, McDonald et al 1996).

Three newer projects of the New Jersey Turnpike Authority, with Mr. Richard Halczli as lead Chief Structural Engineer, are using significant stainless steel. In one, a new 800-foot connecting ramp from the Garden State Parkway to State Route 80 was built and opened in December 1998 [Mumber, 1999]. The aboveground circular ramp used approximately 165 tons of Duplex Alloy 2205 (UNS grade S31803) material supplied by Acerinox in two reinforcing mats. Figure 1 photo shows the ramp under construction with the stainless steel rebars.

A second New Jersey bridge deck project that will also use stainless steel is the Dover overpass on the Garden State Parkway near Essex, New Jersey. It will use about 50 to 60 tons of stainless steel.

The third project is in the final phase of design and approval. It involves the Driscoll Bridge over the Raritan River and will be the largest bridge use of stainless steel in North America. It is projected to use over 1200 tons of stainless material to construct new southbound lanes and to re-deck the northbound bridge deck.

The New Jersey Turnpike Authority has stated that stainless will be standard construction practice on high traffic toll-road decks in the future, with the rationale to substantially eliminate the corrosion damage to the bridges caused by an extensive use of road salt in winter months.

NEW YORK

New York State DOT had planned to use solid stainless steel rebar in two new bridge decks located on I-85 near the New York State and NYS Office Campus complex. Empire Specialty Steel and SSINA had offered to offset the incremental cost of stainless steel rebar as compared to epoxy-coated rebars on the first bridge, which would have used approximately 32 tons of stainless rebar. The second bridge, which was submitted for TEA 21 funding by NYS and was expected to be constructed in 2000 on I-85 over the Normanskill Creek, was to have used about 30 tons of solid stainless rebar. However, the use of stainless rebars was cancelled for these bridges due to inadequate funding to subsidize their higher cost.

For a third deck, the Putnam Road Overpass near Duanesburg, New York, the State Thruway Authority plans to use 30 tons of Nuovinox stainless-clad steel reinforcing bar. Deck design took place in the first quarter of 2000, with construction scheduled to begin in 2001 (Loftus 1999).

Interest in using stainless rebars continues in the Albany area, and NYSDOT and District 11 have made new inquiries about potential rebar applications on Long Island.

NORTH CAROLINA

North Carolina received $430, 000 from IBRC to use Nuovinox bars in replacing a NC 24 bridge over White Oak River.

NORTH DAKOTA

North Dakota received $58, 000 from IBRC to use Nuovinox bars in a new bridge on I-94 at Valley City.

OKLAHOMA

Oklahoma received $300, 000 from IBRC to use Nuovinox bars in a new bridge on I-35 over the Chickaskia River.

OREGON

More than 75 tons of type 316LN stainless rebar were used for the Brush Creek Highway Bridge, constructed in 1998. The bridge is an arch bridge with stainless steel reinforcing bar in the deck and standard black bar in the arches. PVC sleeves are used at all stainless steel – black steel intersections to provide electrical isolation and prevent any problems that could be caused from dissimilar corrosion potentials. The maximum size of the stainless steel available was 32-foot #18 bar, as provided by Empire Specialty Steel Corp. The bars were fabricated on site by Far West Steel, and were used with stainless steel wires and chairs, also provided by Empire. The Oregon Department of Transportation (ODOT) is confident that the Brush Creek Bridge will last its design life of 120 years, with little change expected in the bridge over that time (Cryer 1999).

A second application in Oregon used 125 tons of Type 316LN stainless reinforcing bars for the Smith River Bridge constructed in 1998 on Highway 101 north of Reedsport. This bridge is of precast concrete beam construction with epoxy-coated post-tensioning strands and stainless steel reinforcing bars in the beams. Specifications for handling the stainless steel bars, which were also fabricated by Far West Steel, were the same as for the Brush Creek Bridge. A factor in the expected life of the Smith River structure is the use of epoxy strands, as their life is undetermined (Cryer 1999).

A third bridge deck with stainless steel reinforcing bars (Haynes Inlet) is to be built in Oregon, while a fourth has been designed with stainless bars (Spencer Creek). The Haynes Inlet Bridge will use about 370 tons of stainless steel, which is being supplied by Empire Steel. The Spencer Creek project is undergoing environmental hearings (unrelated to construction materials) and will not be released for bid until after the hearings (Frank Nelson, Oregon DOT).

Additional applications for stainless steel are included in the Haynes Inlet Bridge: hinge pins (Nitronic 60 alloy for its corrosion and galling resistance), plate (duplex 2205), and fastener stock (Type 316LN). The pin and hinge assembly is part of the effort to control future seismic shifts. This project will use nearly 50 tons of stainless material.

Oregon has also evaluated some Nuovinox bars. In these initial evaluations, the bars had a number of negatives, such as lack of rib definition, debonding of the stainless "skin" in bend tests, thinning of the stainless skin at various bar location, and inconsistent skin thickness along the bar.

SOUTH CAROLINA

The South Carolina Department of Transportation received $184,500 from IBRC for a bridge deck on SC 73 in Myrtle Beach (Ocean Drive). The bridge will use slightly over 30 tons of 316LN stainless steel reinforcing on a 40 by 60-foot (12.2 x 18.3m) deck; this reinforcing has been shipped by Empire Steel as Grade 420. Bar sizes included 13, 16, 25, and 29 mm (#4, 5, 8, and 9). Concrete parameters were not adjusted due to the stainless bars, but inhibitors were used in portions of the bridge without stainless rebars. A technical evaluation is being led by Dr. Popov at the University of South Carolina. (Koon 2000)

TEXAS

The Texas Department of Transportation (Sarcinella 1999) is funding a research project to look at the various coatings available for reinforcing steel, including stainless cladding. Having just completed a 7-year project on epoxy-coated reinforcing bars, TXDOT will be performing macrocell, immersion, pull-out, and acoustic emission tests on galvanized, PVC, non-flexible epoxy, nylon, and stainless-clad coatings to compare the effectiveness of these coatings as compared to epoxy. The incorporation of stainless-clad steel reinforcing bars in the project came out of a discussion that TXDOT had with Stelax Industries Ltd., and was ultimately included because a steel mill in Texas is seriously considering using Stelax's Nuovinox technology to produce stainless-clad bars.

VIRGINIA

The Virginia Transportation Research Council (VTRC) is currently conducting an intensive study of stainless-clad steel and copper-nickel clad reinforcing bars, which is intended to expand on the aforementioned FHWA studies. The project, entitled "Laboratory Testing of the Corrosion Resistance of Selected Metallic Reinforcing Bars for Extending the Service Life of Reinforced Concrete Structures" (Clemena 1999), is expected to be completed in the second quarter of the 2001 fiscal year. The Virginia Department of Transportation then plans to construct a bridge deck using stainless-clad steel reinforcing bars, and has received an IBRC grant for a new bridge on Rt 460 over a Rt. 29 bypass.

WISCONSIN

A state project was conducted on State Route 29, east of Wausau, in which dowel bars of various materials and construction were used in a four-lane highway. The bars included 1 ½-in-diameter Type 304 stainless steel dowels, Type 304 stainless steel grout-filled tubes, epoxy resin dowels, and fiber-reinforced polymer (FRP) dowels. The stainless steel dowels were supplied by Slater Steel. All were 18-inches long. Figure 4b shows the cross-section of the grout-filled stainless dowel. The first-year performance has been reported (Crovetti 1999). There were no differences in constructability. Pavement monitoring will continue for four years.

The Wisconsin Department of Transportation (WIDOT) also conducted pull-out and joint-deflection tests on various dowel bars, using the protocol outlined in AASHTO T 253-93 (Anonymous 1997). Stainless steel dowels with both a polished surface and a brushed surface were tested. The brushed samples resisted significantly more load before initial movement than the polished samples, and also retained greater pull-out resistance after initial movement.

More recently, Wisconsin has decided to extend its evaluation of anti-corrosive dowels by evaluating Nuovinox dowels in highway expansion joints on I-39 in Wauchara County. Wisconsin also received $120, 000 from IBRC to use Nuovinox bars in a new bridge on US 12 over the Baraboo River.

OTHER STATES AND OTHER PROJECTS

The Civil Engineering Research Foundation (CERF 2000) is investigating the use of stainless steel dowels, as well as FRP dowels, in highway joints, in order to examine the benefits of replacing traditional mild steel and epoxy-coated dowels with these alternative materials. The stainless steel dowels include Types 304 and 316 steel. The Highway Innovative Technology Evaluation Center (HITEC) program is implementing test sections in Illinois, Ohio, Wisconsin, Iowa, and Kansas. Activities will continue to take place through the year 2003.

In other projects using stainless and/or stainless-clad steel bars, Hawaii, Ohio and Alaska are reportedly evaluating Nuovinox products in either rebar or dowel bar form (Stelax 1999a).

Stainless steel rebars are also being used in some parking garage applications where carbon steel rebars typically incur severe corrosion damage due to water and road salts. The Burlington, Iowa, precaster, Raider Precasters, Inc., for example, uses Type 304L stainless steel V-bars at the joints between adjacent precast double-tee beams. An example is the parking garage at State Farm Insurance's headquarters in Bloomington, Illinois. Other parking garages using Type 304L rebars are in Exeter, New Hampshire, Brighton, Massachusetts, and Hartford, Connecticut.

Other installations include several coastal installations of piers done by the Navy during the 1980s on the West Coast Nitronic 60 steel was primarily used. The Navy's satisfaction is evidenced as it continues to specify this material for similar installations. An installation at the

Norfolk Navy Yards was completed in 1997 with some 200,000 lb of Nitronic 60 rebar and 400,000 lb of high strength Nitronic 60 wire for strand cable.

CANADA

One thousand kilograms (12.1 tons) of Grade 400 type 316LN stainless steel reinforcing bars were installed in a bridge deck on Highway 407 over Mullet Creek in Toronto, where construction was completed in 1996. The fabricator and installer of the rebars was Harris Rebar, and the producer was Empire Specialty Steel Corp. Objectives of the Mullet Creek installation were to examine the feasibility of using stainless steel reinforcing bars on a large-scale project under normal contracting methods, and to assess the added durability and corrosion resistance that stainless steel implies. Probes have been inserted into the deck to monitor the corrosion-cell activity. Monitoring is being done by the Ontario DOT through Corrosion Ltd. of Toronto, and latest reports indicate that the bridge remains electrically inactive. The Mullet Creek Bridge was chosen because it typifies many highway bridges, and because a twin bridge located in the westbound lane could be installed with epoxy-coated reinforcing bars for comparison. The deck has a span of 21 m (69 ft), a width of 12 m (39 ft), and a deck slab depth of 235 mm (9.25 in). The concrete cover over the reinforcement was specified as 60-100 mm (2.4-3.9 in). Isolation of the stainless steel from other metals was accomplished using sleeves (Hope et al 1998, Stainless Bulletin 1999). Figure 1 shows two photos of the stainless steel bars in place before the concrete deck was placed. The chairs for the rebars are plastic. However, the U-bars in the concrete stringers are epoxy coated. Stainless steel wire ties were used.

With issues still unresolved about epoxy-coated reinforcing bars, and with the Canadian Highway Bridge Design Code suggesting that bridge design life be extended to 75 years (from 50 years), stainless steel was chosen as a means of possibly achieving the high design life without major rehabilitation measures. The report describing this project states that no cracking observed in the structure could be attributed to the use of stainless steel, and that the use of stainless steel was found to be viable with no unusual problems detected. Future work planned for this project includes the continued monitoring of the Mullet Creek structure to determine its corrosion performance, as well as developing ideas on taking better advantage of stainless steel for future projects by reducing the amount of steel and concrete used (Hope et al 1998).

A project involving the Church St. Bridge in Ajax, Ontario (Highway 401, East of Toronto) was completed in the spring of 1999, using about 175 tons of Type 316LN stainless steel reinforcing bars ranging from 16 to 30 mm (#5 to #10 bars) in size (Stainless Bulletin 1999). The bars were supplied by Empire Specialty Steel and fabricated by Harris Rebar.

Approximately 20 to 25 repair and rehabilitation projects have reportedly utilized stainless steel in both Ontario and the province of Alberta. A partial listing of these projects, provided by Empire (Al-Tech) Steel, follows. Usage of stainless steel rebar on most of the repair projects has been in the range of 2.5 to 15 tons per job. An additional four to six bridge decks were projected to be let for construction bids by the Ontario Ministry in late 1999 and year 2000.

Empire (Al Tech) Stainless Steel Rebar Applications (Partial List)

- Mullet Creek Bridge / Hwy 407 (Halton Hills, ON)
- Church St. / Hwy. 401 Bridge Overpass (Ajax, ON)
- CNR Bridge over Black River Mt. (Albert, ON)
- Hwy 406 @ St. Davids Rd. / Gibson Ln. (St. Catharines, ON)
- Hwy 11 & Hwy 141 Bridge (Port Sydney, ON)
- Molson Park Interchange @ Hwy 400 (Barrie, ON)
- Lincoln Alexander Pkwy / Dartnall @ Mud St. (Hamilton, ON)
- Hwy 518 over Hwy 11 Overpass (Elmsdale, ON)
- Cadotte River Bridge (Peace River, Alberta)
- Marten River Bridge (Peace River, Alberta)
- Burlington Skyway (Burlington, ON)
- Muskrat River Bridge (Carlton Place, ON)
- QEW/Guelph Line Interchange (Guelph, ON)
- Erin Mills @ QEW Overpass (ON)
- Boivaird Drive Bridge (Brampton, ON)

The Ontario Ministry has declared that stainless steel rebar will be the standard practice in preference to epoxy-coated bar on their high-traffic 400 series road system. There are now some 20 installations, including new decks as well as repair projects in damaged installations where either epoxy or carbon steel reinforcement had been used and failed by corrosion and concrete spalling. The usage for projects in the year 2000 and 2001 is projected to have a rate of 500-600 tons annually for roads within the Ministry's responsibility (about 20 percent of the roads in the province). These figures are from a ministry meeting held with stainless steel industry officials in August 1998. As a recent example, Empire Steel received a contract in May 2000 for 85 tons of type 316 LN rebars for an interchange project.

The Ontario Ministry has also evaluated Nuovinox bars, with the same results as experienced in Oregon.

MEXICO

Knudsen and Skovsgaard (1999) highlighted the performance of a stainless steel reinforced concrete pier in Progreso, Mexico. The pier was installed in 1939 and reinforced with the equivalent of a 304-grade stainless steel. A similar pier in the same coastal location built in the 1960s with carbon steel as reinforcement has disintegrated while the stainless pier has survived in excellent condition. Various corings and evaluation of concrete were carried out at several locations along the pier. Neither the concrete nor the 304 stainless show any signs of deterioration.

UNITED KINGDOM (citations from www.stainless-rebar.org)

Type 316 stainless steel reinforcing bars were used for replacement columns and precast concrete beams in a sea-front structure restoration in the mid-1980s in Scarborough, UK.

An underpass at Cradlewell, UK uses 240 tons of Type 316 stainless steel reinforcing bars in a road slab, constructed in 1995.

In 1996, five bridges on the M4 motorway in the UK required reconstruction because of carbon steel reinforcing bar corrosion. Selective use of Type 304 stainless steel reinforcing bars (27 tons) was implemented for safety parapets and for tying these into the main structure.

The Guildhall Yard East project in London, England (1996) utilized over 140 tons of Type 304 stainless steel reinforcing bars. Although the new structures will not be exposed to de-icing salts or to a marine environment, the design engineers were looking for a very long design life, in keeping with the famous historic buildings on the site.

Other U.K. stainless steel reinforcing bar applications include the restoration of the North Wing of John Nash's Cambridge Park Terrace at Regent's Park, London; the British Library, London; the Ilfracombe Pavilion, North Devon (4.8 tonnes [5.3 tons]); and Knucklas Viaduct, North Wales (9 tonnes [9.9 tons]).

Other European

The Schaffhausen Bridge in Switzerland, constructed in 1995 across the Rhine River, contains Type 304 and Type 2205 duplex stainless reinforcing bars in critical parts of the structure. An important consideration in selecting stainless steel reinforcing bar in areas affected by de-icing salts was the minimization of repair and disruption costs. More than 13 tonnes (14.3 tons) of stainless steel reinforcing bar (Types 304 and 2205 combined) were used (www.stainless-rebar.org).

AUSTRALIA

Stainless steel reinforcing bars were selected for the Sydney Opera House forecourt restoration project around 1990. The engineers of the New South Wales Government Public Works specified Type 316 stainless steel reinforcing bars, and 14 tons were supplied for the project (www.stainless-rebar.org).

MIDDLE EAST

Harbor facilities in the United Arab Emirates. and Qatar used 25 tons of type 316 stainless steel reinforcing bars as reinforcement in wharf posts in 1998 (www.stainless-rebar.org).

VI. CORROSION RESISTANCE OF STAINLESS STEEL REINFORCING

Stainless steel reinforcing has application due to the improved long-term cost benefits afforded by its corrosion resistance. This section describes the corrosion factors and related experimental studies that affect the application of stainless reinforcement.

As summary, discussions in this section show the excellent performance of stainless steel rebar in immersion and electrochemical corrosion testing. Austenitic stainless steels tested consistently out-performed the other bars tested, such as carbon steel, black, epoxy-coated, galvanized, and other metallic coated bars. At high levels of chloride contamination, type 316 showed greater corrosion resistance than type 304. Galvanic corrosion studies, related to the use of stainless in combination with other materials, show that the galvanic couple formed by Type 316 rebars and carbon or black bars did not indicate an increase in corrosion rate. The results further suggest that this couple may even be less severe than that formed between active and passive carbon steel, as with repaired carbon-steel systems. Galvanic issues need further investigation with Type 304 rebars, where results have shown some increase in cell corrosion.

PRINCIPLES OF CORROSION

Corrosion is the reaction of a material to its environment. As concrete is typically a high pH environment, its reaction with reinforcement results in the formation of a passive oxide layer. The stability of this film is influenced by the ingress of water, oxygen, and chlorides through the concrete. As water and oxygen reach the concrete- rebar interface, further oxidation occurs resulting in a greater volume of corrosion products creating tensile stresses. As these stresses induce cracking of the concrete, transport of reaction products to the surface increases.

If the cracked concrete were to become submerged and remain so, rebar corrosion would be minimal. This is due to the slow transport rate of O_2 in the liquid water phase in comparison with the rate in the vapor phase, i.e. through porous concrete. Corrosion products form in continuously saturated concrete, and remain in the water and do not deposit and induce a tensile force at the concrete/rebar interface. When, more typically however, a structure endures wet/dry conditions, the most severe corrosion conditions are present. Not only is O_2 transport to the steel surface much quicker, but deposition and compaction of corrosion products occur when the water evaporates, creating tensile stress and eventual spalling of the concrete.

ROLE OF CHLORIDES

Chlorides play the most significant role in reinforcement corrosion. Chloride is a well-known passivity destroyer. It results in a local breakdown of the passive film and an increase in the corrosion rate of steel and stainless steel in neutral and alkaline solutions. Chlorides may be introduced to the concrete in many ways. They may exist as an impurity in the water or in the aggregate in the initial mixture, or intentionally be added as a quick-set component to enhance the curing process. After curing, chlorides may be introduced through saline exposure in the form of spray, mist or fog, or by the use of de-icing salts.

As local breakdown of the passive film occurs, the production of Fe^{+2} ions from the iron corrosion reaction attracts more Cl^- ions to the area. As these ions react with water, hydrochloric acid is formed reducing the pH of the solution. Some iron ions also may react with water, forming a porous iron hydroxide that deposits on the surface of the rebar, thus increasing the interfacial stresses. These reactions work together to perpetuate the corrosion process.

ROLE OF CARBONATION

Carbonation, which reduces the pH of the concrete and pore solution, is also a concern in the corrosion of concrete reinforcement (Schiessl 1988). The CO_2 in ambient air may react with the calcium hydroxide in the concrete resulting in a reduction in pH to a value as low as 9. Other alkaline components in the concrete will react similarly with carbon dioxide. The rate of carbonation and the depth of penetration will depend on the composition, compaction, and curing conditions of the concrete as well as the environmental conditions. As mentioned above in the case of oxygen diffusion, the rate of carbon dioxide diffusion in water is approximately 10^4 times lower than in air, i.e., open pores. Therefore, saturated concrete will slow the progress of carbonation due to a decrease in diffusion rate.

CORROSION EXPERIMENTS

Literature reviews of research on the corrosion of stainless steel used as reinforcement in concrete have been prepared by the European Federation of Corrosion (EFC) Working Party on Corrosion of Reinforcement in Concrete (Nurnberger 1996), and by Wiss Janney Elstner and the FHWA (McDonald and colleagues 1995, 1996). These provide overviews of the research performed to that time. Several of the investigations discussed in those reviews, and more recent results, are summarized below. These investigations have examined the effects of chloride- and carbonate-contaminated concrete, of pH level, of galvanic action, and of welds on the overall, pitting, and crevice corrosion modes of various grades of stainless steel rebars. These grades included austenitic Types 304, 304L, 315, 316, and 316L; ferritic Types 405 and 430; martensitic Type 410; duplex alloys; and superaustenitic alloys. Other bars included in some of the investigations were epoxy-coated bars, galvanized bars, and other metallic-coated bars.

Stainless-clad rebars were seldom included in early corrosion investigations because a successful practice for manufacturing them was not available until the relatively recent introduction of the Stelax practice in the U.K. Stainless-cladding for corrosion resistance has been extensively practiced, however, in the petrochemical and utility industries, especially for piping and tanks (Smith and Celant 1998). A recent application of stainless-clad pipes is in China's Three Gorges Dam project (ENR 1999).

The more recent (FHWA 2000) report describes both corrosion control measures and tests of corrosion-resistant reinforcing bars. While the emphasis is on epoxy-coated rebars and other coated-bar systems, five grades of solid stainless steel bars (304,316,317, Nitronic 33, and XM-19) and stainless-clad bars (304 steel cladding) were subjected to screening tests. After the screening tests, the solid Types 304 and 316 rebars were selected for in-concrete corrosion testing. This latter testing included a 15-percent saltwater solution with a chloride concentration estimated to be about 5x greater than that of normal seawater. The following two paragraphs are from the conclusions (p. 71) of the FHWA report:

> "The Type 316 stainless steel bars should be considered during the design stage as a potential corrosion-protection measure to achieve a 75- to 100-year crack-free design life. The additional cost may be justified by a life cycle cost analysis. This is especially true for structures that carry a significant amount of traffic and where repairs are difficult and/or costly and closures are a problem. An alternative to solid bars may be a stainless-clad bar."

> "The Type 304 stainless steel bars had excellent performance when straight bars were cast in uncracked concrete. However, when bent bars were used with a black bar cathode, moderate corrosion resulted. Therefore, Type 304 stainless steel bars are not recommended, particularly in combination with a black bar cathode."

CORROSION FACTORS

Rebar Deformations

Although stainless steel is excellent at resisting general or uniform corrosion, it is susceptible to localized corrosion due to the breakdown of the passive film. The most well known "passivity destroyer" is the chloride ion. As this is the primary culprit in the corrosion of reinforcement, the potential for crevice and pitting corrosion of stainless steel rebar must be considered. Crevice corrosion is the result of an increase in the corrosiveness, often a decrease in pH, of the local environment surrounding an area subjected to a crevice. The solution within a crevice is stagnant. The corrosion products with a positive charge are trapped, attracting ions of a negative charge, i.e. Cl^-, resulting in an auto-catalytic, or self propagating, situation. It is unclear if the ribs on reinforcement form a crevice sufficient to influence the local corrosion properties, although results in a state of the art report, "Stainless Steel in Concrete", (Nurnberger 1996) suggest they may. In that study, the corrosion resistance of several stainless steels and an unalloyed steel control was compared for both plain and deformed bars in the welded and un-welded condition. In general, the deformed stainless bars did not perform as well as the plain stainless bars, and pitting was observed near the deformations. This suggests that the deformations may provide an initiation site for crevice corrosion. The unalloyed material was observed to undergo more general attack.

Joining Issues

Welding of stainless steel rebar may locally decrease its corrosion resistance. This effect was noted in the abovementioned state-of-the-art report. During welding, the materials may be heated through the range of temperatures where it is thermodynamically possible to form carbides at the grain boundaries. The carbides form with alloying elements responsible for the formation of the passive film, such as chromium. An area of chromium depletion occurs in the regions surrounding the grain boundaries, making these areas more susceptible to attack. The severity of the grain boundary attack depends on the aggressiveness of the electrolyte (Sedriks 1996). It is unclear if the environment present in concrete would induce sensitization.

Welding may also cause the formation of a galvanic couple during repairs or joining of dissimilar materials. Although the galvanic couple between stainless and carbon steel was found to be less severe than the couple formed for active and passive carbon steel (Bertolini et al 1998), stainless samples with a high temperature scale oxide film developed a more significant galvanic couple. These results suggest that caution is essential to maximize the performance of welded stainless rebars in concrete.

Welding of stainless clad rebar will result in the same issues discussed above. Dilution of the alloying elements may occur within the weld resulting in a region less resistant to corrosion. If the dilution is significant, not only could sensitization be a concern, but a galvanic couple could form around the weld. Welding procedures are not well established to address this issue, as discussed in Section IV. It is clear that further investigation is required to assess the effect of welding on the corrosion resistance of clad samples.

Cladding Thickness Issue

The Nuovinox minimum cladding thickness of 500 μm (0.5 mil) has been adequate in trials reported to date to prevent corrosion, but the optimum cladding thickness for corrosion resistance and long-term life has not been established.

Fatigue Issues

Because a major reason to use stainless steel is its corrosion resistance, a number of fatigue tests have been conducted in a chloride environment. Johansson and Groth (1990) report pulsating tension fatigue data and rotating beam bending fatigue data for several stainless steels. The data were accrued from European and Japanese sources. None of the data was specifically from reinforcing bars, but some of the conclusions are salient to reinforcing bars. In the tests reported, there were, unfortunately, no carbon steel control bars. Overall, using twenty million cycles as a fatigue limit, Types 304LN, 316LN, and 2205 stainless steels were found to have a rotating-beam fatigue strength in air that was about equal to their yield strength and equal to 0.45 to 0.62 x their tensile strength. As the pH of a 3-percent NaCl testing environment decreased, however, the fatigue strength also reduced. At pH=7, the ratio of fatigue strength to the (air environment) tensile strength was 0.42 to 0.58; at pH=3.0, the ratio was 0.25 to 0.44. At pH=1, the ratio was 0.06 to 0.25. As pH decreased, the loss in rotating-beam fatigue strength was greatest with the Type 304LN steel and least with the duplex 2205 alloy. The higher-strength 2205 alloy in all cases exhibited greater fatigue strength (as a ratio of tensile strength) than did 316LN steel. In pulsating tension tests on 2205 alloy, the fatigue strength at twenty million cycles was a stress range of 0.7 x tensile strength in air and decreased only negligibly to 0.65 x tensile strength in an 0.06 percent NaCl environment at temperatures up to 80°C.

For welded stainless steel, Fisher's data (Fisher 2000) is applicable. It shows that welded plates (both groove welded and fillet welded) of 3/8- and ½-inch-thick structural grade superaustenitic stainless steel (UNS No. 08367) meet AASHTO fatigue Category B with longitudinal-fillet and groove weld details and Category E with transverse fillet-welded attachments, and are at least equal in fatigue resistance to similar weldments in carbon-manganese steel typical of carbon-steel reinforcement. Fisher did not conduct tests in a chloride environment.

The authors are not aware of fatigue tests having been conducted on stainless-clad Nuovinox bars, either in air or in a chloride environment. This is a topic where study would be useful in order to demonstrate that fatigue cracking does not occur and that separation does not occur under cyclic load between the stainless cladding and the compacted carbon-steel core. Such cracking or separation could expose the carbon-steel core to general corrosion.

CORROSION IN CHLORIDE- AND CARBONATE-CONTAMINATED CONCRETE

Treadaway, in a 10-year UK study (Treadaway, Cox and Brown 1989), compared stainless steel and other reinforcing bars in concrete with various chloride levels. The rebar specimens were ferritic (Types 405 and 430) and austenitic (Types 304, 315, and 316) stainless steel, and unalloyed, weathering, and galvanized steel. Bare high-yield carbon steel bars were used as the control. The specimens were descaled. Chloride was introduced in levels of 0 to 3.2 mass %, and the prisms were exposed to natural environments. The concrete cover was 10 and 20 mm (0.4 and 0.8 in). The reinforcement durability was estimated by evaluating the extent of concrete cracks, and rebar weight loss and degree of pitting.

Severe corrosion, both loss of cross section and localized pitting attack, was seen on the high-yield steel bars in high-chloride containing concrete (2-3 wt.%). Weathering steel bars suffered similarly, with more pitting than general corrosion. Compared with high-yield steel bars, galvanized steel bars led to only a slight delay in cracking in high-chloride-containing concrete, but had better performance in low-chloride uncarbonated concrete. The ferritic stainless steel bars (Types 405 and 430) had increased time to cracking in low-chloride level concrete. But, at high-chloride levels, extreme pitting occurred in the bars and was concentrated at a few points on the surface. Some pitting even occurred at low chloride levels. The austenitic stainless steel bars (Types 304, 315, and 316) demonstrated high corrosion resistance in all situations, and no serious corrosion was observed on any of the bars. A Type 304 steel bar exposed to the highest levels of chloride did exhibit slight pitting, however. In light of these results, the investigators advised further study into the crevice corrosion susceptibility of Type 304 bars before their placement into a high-chloride-containing environment.

Pastore and his colleagues (Pastore and Pedeferri 1991; Pastore et al 1991; Bertolini et al 1993) used electrochemical methods to study the effect of chloride contamination on corrosion behavior. Austenitic Types 304 and 316 and duplex stainless steel bars were placed in concrete with up to 3 wt.% chloride contamination. Open-circuit potential measurements, corrosion rate determinations by linear polarization, and potentiostatic tests were performed. All samples remained in the passive state with no significant differences in their corrosion behavior.

Another study by Pastore's group (Bertolini et al 1996) examined localized corrosion of rebars in chloride-containing solutions. The study used austenitic stainless steel Types 304, 304L, 316, and 316L; martensitic stainless steel Type 410; duplex stainless steel; and superaustenitic stainless steel, with carbon steel as the control. The chloride-containing solutions simulated the pore solution in alkaline and carbonated concrete. The critical chloride content at which pitting was observed was determined at a potential of +200 mV_{SCE} in solutions with pH values ranging from 7.3 to 13.9, at temperatures of 20 and 40°C. Chloride concentration varied from 0 to 10 percent.

With a pH of 12.6 resulting from a solution of saturated $Ca(OH)_2$ at 20 °C, corrosion began on carbon steel with chloride concentrations of 0.1-0.6 percent; on martensitic stainless steel Type 410 at 2 percent; and on austenitic stainless steel Types 304L and 316L at concentrations higher than 5.5 percent. Austenitic Types 304 and 316 steels did not show attack with concentrations even as high as 10 percent; and no localized corrosion was observed on the duplex steel or superaustenitic steels with up to 10 percent chloride concentration. At a lower pH of 9.0 at 20°C, the difference in critical chloride concentration narrowed for the martensitic, austenitic and duplex stainless steels, with some austenitic alloys out performing the duplex alloy. The critical chloride content was around 3 percent for austenitic Types 304L, 316, and 316L, just above 2.5 percent for the duplex alloy, slightly below 2.5 percent for austenitic Type 304 and about 2 percent for the martensitic Type 410. With a pH of 13.9, a beneficial effect of alkalinity on chloride-induced corrosion was observed both on carbon steel and stainless steel. The critical chloride concentration for carbon steel increased to 6 percent from 0.01-0.6 percent with a 12.6 pH, and the critical chloride levels for all the stainless grades exceeded 10 percent.

These results indicated the benefit of using austenitic stainless steels in high chloride environments even with some level of carbonization. The martensitic alloy Type 410 may be appropriate for use in carbonated concrete where levels of chloride would remain below 2 percent. The superaustenitic stainless steel had complete corrosion resistance within the parameters of the experiments.

Rasheeduzzafar (Rasheeduzzafar et al 1992), in a 7-year exposure program, measured the corrosion resistance performance in chloride-contaminated concrete of Type 304 stainless-clad steel bars and of bare, galvanized, and epoxy-coated mild steel rebars. Besides the type of rebar, chloride concentration in the concrete was the only variable. The rebars were placed in prismatic samples of concrete with a 0.45 water-cement ratio. Three levels of chloride (0.6, 1.2, and 4.9 percent mass of cement) were introduced as sodium chloride in the mix water. The exposure site was in Eastern Saudi Arabia where the summer temperatures were typically around 45-50°C with concrete surface temperatures reaching 65 to 70°C due to radiant effects. Although saline effects of the Arabian Gulf are present with high humidity, actual rainfall was extremely low, so these samples were not exposed to wet/dry cycles or immersed. The concrete condition was evaluated at 24 potential crack locations on a six-point severity scale. With bare mild steel, there was significant concrete cracking at all chloride levels. This was also true with galvanized steel, although cracking was slightly less severe. Concrete with epoxy-coated bars showed no cracking for chloride levels of 0.6 and 1.2 wt. percent, but suffered wide cracks with a 4.9 wt. percent chloride content. In contrast, with the stainless-clad steel bars, no cracking was observed at any chloride level.

In a major study sponsored by the Federal Highway Administration (McDonald et al 1996), the corrosion performance of 24 types of solid and clad reinforcing bars was evaluated. The evaluation was part of a project to develop corrosion-resistant reinforcing bars permitting concrete structures with 75- to 100-year design lives.

Fourteen types of clad bars were screened and the four best types were then compared with ten types of bare bars. In the initial screening, the clad bars were subjected to 6-hour cycles consisting of immersion for 1.25 hours and air drying for 4.75 hours. The immersion solutions had two pH levels: pH 7 (3 percent NaCl) and pH 13 (0.3N KOH + 0.05N NaOH + 3 percent NaCl). The bars were cycle-tested for 28 days in either a straight or bent condition, either as-received, abraded, or with holes drilled through them. Later, the bare bars and the select clad bars were subjected to the original solutions and to two other pH 13 solutions: (0.3N KOH + 0.05N

NaOH + 9% NaCl) and (0.3N KOH + 0.05N NaOH + 15% NaCl). Moreover, they were tested only in the bent condition, as this was seen to be more severe in the initial testing, and either as-received or with holes. Bars in the pH 7 solution were tested for 90 days. Bars in the pH 13 solutions were tested for 168 days; 56 days in the 3 percent NaCl solution, followed by 56 days in the 9 percent NaCl solution, followed by 56 days in the 15 percent NaCl solution.

The bars were evaluated by polarization resistance measurements and by visual assessment. The polarization resistance was measured by linear polarization ±10mV from the equilibrium corrosion potential: (a) when the bars were first immersed; (b) after 1, 7, 28, 56, and 90 days of testing in the pH 7 solution; and (c) after 1, 7, 28, and 56 days, and periodically to 128 days in the pH 13 solution. The half-cell potential was also measured using a silver/silver chloride reference.

The following performance lifetimes were calculated based on the experimental results, and by assuming concrete cracking occurs when a metal loss of 0.0254 mm (0.001 in) due to corrosion is achieved. For black, zinc-clad, and/or zinc-alloy-clad bars, cracking would occur within 1 year. Copper clad bars may attain a lifetime of 5 years. Stainless–clad bars may experience cracking after about 23 years of exposure in the most severe chloride concentrations tested. In lower levels of chloride contamination, it may take up to 50 years for cracking to occur in stainless-clad bars. Solid stainless steel bars and solid titanium bars had high polarization resistance values in all the test solutions suggesting time to cracking of 100 years.

Nurnberger et al (1993) made electrochemical determinations of pitting corrosion in concert with comparative field tests. Austenitic, duplex, and ferritic steel bars were tested with unalloyed steel bars for comparison. The bars were tested in both welded and unwelded conditions. Chloride contents of 1.3 percent and 5 percent were added, and half of the reinforced concrete samples were contaminated with carbonate.

In these tests, the austenitic and duplex stainless steel bars with mass Cr contents >11 percent were the most resistant bars to pitting corrosion. The most severely attacked bars were ferritic steels with a mass chromium content of < 7 percent. In the carbonated concrete, the bars with Cr contents >11 percent again showed better corrosion resistance than the samples with < 7 percent

Cr. The pitting corrosion potential decreased with increasing chloride content in the concrete and was more negative with carbonate-contaminated concrete than with alkaline concrete.

Welding had a negative impact on the corrosion resistance of the test samples. For the ferritic stainless bars, a decrease in pitting potential was observed, as well as a formation of single pits starting at scores that were close to the ribs. The unalloyed bars, however, showed more general attack and had wide pits, with no difference in the pitting potentials. In general, the welded reinforcing bars corroded more than the unwelded bars; this was more pronounced in alkaline concrete than in carbonated concrete.

In the field tests, the unalloyed steel bars corroded in carbonate-contaminated and in chloride-contaminated concrete, with the strongest attack occurring in concrete that was both carbonate- and chloride-contaminated. Unwelded ferritic stainless steel bars displayed better corrosion resistance than the unalloyed steel bars. No attack was seen in either carbonate-contaminated concrete or in chloride-contaminated alkaline concrete. However, with both carbonate- and chloride-contaminated concrete, pitting occurred with both welded and unwelded ferritic stainless steel bars. Additionally, local pitting corrosion occurred along the weld line on the welded ferritic steel bars, with the depth of pit increasing with increased chloride content. Even though the overall corrosion resistance of the ferritic stainless bars was better than for the unalloyed steel bars, pitting at the weld lines was actually deeper for the ferritic bars. With the austenitic steel bars, both welded and unwelded, no corrosion appeared regardless of whether the concrete was carbonate-contaminated, chloride-contaminated, or both.

Sorensen, Jensen, and Maahn (1990) also made electrochemical investigations on rebar samples, specifically on ribbed samples of black steel and cold-rolled Type 304 and 316 stainless steel bars that had been embedded in mortar. Samples both with and without welds were tested with no attempt to remove deposits resulting from the manufacturing or welding, but were degreased prior to embedment. Chlorides were introduced into the initial mortar mix in quantities between 0 and 8 wt. percent cement and by ingress.

The corrosion attack was more localized on the stainless steel bars than on the black steel bars, but the critical chloride concentration was more than 10 times higher than for the black steel. The Type 316 steel bars performed slightly better than the Type 304 steel bars. Welding was found to reduce the critical chloride concentration to 1/3 to 2/3 of that for the unwelded stainless bars. This was attributed to the combined effect of oxidation and insufficient compaction of the concrete around the weld. The latter case can leave voids, which create a crevice that acts as the initiation site for corrosion attack. The potentiodynamic and potentiostatic polarization results of the study suggest that Type 304 stainless steel bars, even though inferior to Type 316 bars, are sufficient for application in chloride environments. In the same study, some stainless-steel reinforced samples were stored outside for 5 months, and afterwards exhibited essentially no signs of corrosion.

GALVANIC CORROSION

Galvanic corrosion results from the preferential corrosion of a material when coupled to a more noble material. The materials must be in electrical contact for the transfer of electrons, and surrounded by a conductive environment to support the transport of ions. The anodic or oxidation reaction, which produces electrons and releases positive metal ions, is equal to the cathodic or reduction reaction, which consumes electrons. Galvanic corrosion can also occur on the same material if a breakdown in the passive film occurs and the corrosion potential of the active and passive states are significantly different. For example, discrete areas of attack, such as a pit, will have a cathodic region surrounding it to consume the electrons released. A galvanic couple can also be induced with a difference in the environmental conditions that influence the change in the corrosion potential of the surface. This is sometimes observed as the "anodic ring" surrounding a patch where the new concrete creates a different environment significant enough to polarize the surrounding rebar resulting in corrosion (Hanley et al. 1998).

It has been suggested that stainless steel may be used in the top mat, which would be first to experience the corrosive environment, with carbon steel in the lower mat to reduce cost. If there is electrical contact between the two mats, however, as with the use of rebar cages or metal chairs prior to pouring the concrete, a galvanic couple, as discussed above, may be produced. If the mats were to remain completely electrically isolated from each other, the use of stainless steel in the top mat would not pose a threat of increased corrosion due to galvanic coupling. Any electrical connection, however, would result in a potential couple. Welded joints of dissimilar metals provide the electrical contact necessary for a galvanic couple. This would result in the preferential attack of the less noble material. The studies that have been conducted to evaluate galvanic corrosion possibilities with stainless reinforcing are summarized below.

Zoob, Le Claire, and Pfeifer (1985) utilized test mats with 12-mm-diameter (0.5 in) bars to study galvanic action between Type 304 stainless steel bars and black steel bars. The bars were cast in concrete slabs with a 0.50 water-cement ratio and concrete covers of 25 to 50 mm (1 to 2 in). Each week for 48 weeks, the samples were ponded in a 15 percent NaCl solution for four days at 16-27 °C (61-81 °F) and then dried for 3 days at 38 °C (101 °F). The upper and lower mats of the steel bars were electrically connected so that macrocell corrosion current could be measured. The black bars corroded severely, with observed cracking of the concrete. They had an average maximum current density of around 100 mA/m^2 (9.3 mA/ft^2). In contrast, the slabs with Type 304 steel bars had no measurable macrocell corrosion current, and no visible corrosion after testing. The total soluble chloride after testing was 2.1 wt.% at the level of the bars with a 25-mm (1 in) cover.

More recently, Bertolini et al. (1998) addressed the issue of galvanic corrosion with Type 316L stainless steel reinforcement coupled to carbon steel reinforcement. The steel reinforcing bars were embedded in concrete; in one case the concrete had 3 wt.% chloride added as $CaCl_2$ in the water mix and, in a second case, the concrete's water mix had no chloride. In the tests, a carbon steel bar embedded in the chloride-containing concrete was coupled with a carbon steel bar in chloride-free concrete, a 316L bar in chloride-free concrete, and a 316L steel bar in chloride-containing concrete. The open circuit potential and the corrosion rate were measured for 10 days with the samples exposed to a temperature of 25°C and a relative humidity of 95-98 percent. The corrosion rates were determined by linear polarization in the range of +/-10mV at a scan rate of 10 mV/min. After the bars were coupled, the potential and macrocouple current density were measured. The relative humidity was held at 95-98 percent for 15 days and then decreased to 65-75 percent. Some of the 316L bars were heat treated for the study.

The free corrosion potential for the 316L bar in the chloride-containing concrete was approximately 300 mV higher than for the carbon steel bar, but in chloride-free concrete, the free corrosion potential was slightly higher for the carbon steel bar, and with no oxide scale. The corrosion rates were similar with the chloride-free concrete, but in chloride-containing concrete, the corrosion rate for the 316L bar was approximately two orders of magnitude lower than for the carbon steel bar.

After the specimens were coupled, the corrosion rate of the carbon steel bar in chloride-containing concrete increased less when attached to the 316L steel bar than when attached to a passive carbon steel bar. Thus, coupling effects between a 316L steel bar and a carbon steel bar may actually be less severe than the surrounding passive regions, which would normally occur during rebar corrosion. The 316L bars that had been heat treated and coupled to carbon steel bars, however, did produce current densities on the order of or slightly higher than non-heat-treated bars. This may be a concern if 316L steel bars are to be welded, although the investigators felt the areas affected by welding may be small.

Knudsen et al. (1998) also performed a study addressing galvanic coupling. They studied using Type 316 stainless steel bars in the most corrosion-prone areas of a structure, while using traditional carbon steel bars in other regions. The formation of galvanic couples would be expected to be a concern in these instances. Test samples contained five rebars, either 316 steel or carbon steel, embedded full length in concrete with a w/c ratio of 0.5. Additionally, two shorter bars of either carbon steel or 316 steel, corresponding to 5 to 10 percent of the total steel volume, were embedded in the samples with a MnO_2 reference electrode to monitor potential. The samples contained either all carbon steel bars as a control, full-length carbon steel bars at a greater depth than short stainless bars, full-length carbon steel bars at the same depth as the short stainless steel bars; or full-length stainless bars with short carbon steel bars. The samples were exposed to immersion-drying cycles in a concentrated NaCl solution with $Ca(OH)_2$ for two days followed by five days of drying in laboratory air. Measurements of the macrocouple current and of the electrochemical potential were taken when one of the short bars was coupled with the long bars. The results of these experiments were that coupling of corroding carbon steel to passive carbon steel resulted in a greater current density, by a factor of almost 15, than a coupling to stainless steel.

McDonald and colleagues (1998a, 1998b), in a continuation of the FHWA study discussed above, investigated 11 rebar types in concrete when there was an electrical connection between layers of rebars. The types included: black bars, 6 epoxy-coated bars (3 bendable, 3 non-bendable), Types 304 and 316 stainless steel bars, and bars clad with copper, zinc galvanizing, and zinc-rich metallizing spray. The concrete test samples consisted of two layers of reinforcing bars. Each bar in the top mat was electrically connected to two bars on the bottom mat with a 10-ohm resister. Most samples had a corrosion-resistant top mat and a black-bar bottom mat. Some of the samples were precracked by placing a 0.30-mm-thick (0.012in) stainless steel shim to the bar level during casting and removing the shim one day later. These cracks followed the bars for 150 mm (6 in). For all samples, a clear cover of 25 mm (1 in.) was employed. The samples were subjected to specific condition cycling: 3 days drying at 38°C (100°F) and 60 – 80 percent RH, 4 days in a 16 to 27°C (60-80°F) 15 percent NaCl solution, 12 weeks in the 60 – 80 percent RH environment, and 12 weeks continuous ponding in the 15 percent NaCl solution. These steps were repeated for a total of 96 weeks.

After 96 weeks, all of the black bars exhibited severe corrosion with the top concrete surfaces cracked. The epoxy-coated bars also corroded, but their corrosion rates were lower when coupled with cathodes that also were epoxy-coated than when coupled to black bars. Moreover, because these latter tests resulted in a different ranking of the epoxy-coated bars, compared to the solution immersion tests, the solution immersion test was concluded to be an unreliable measure of predicting the corrosion in concrete.

After 96 weeks, almost all of the samples with galvanized steel bars had cracks running parallel with the bars and corrosion products were evident. But the corrosion rates were condition dependent. When galvanized bars were used in both mats, and without precracks, they had a corrosion rate 38 times lower than that of the black bars. When the galvanized bars were coupled to a black bar cathode in uncracked concrete samples, the corrosion rate increased by a factor of 24. With a precrack, however, the corrosion rates of galvanized bars with black bars in the bottom mat increased a further 41 percent. The investigators concluded that caution should be used to avoid electrical contact between galvanized and black bars.

Most of the zinc-metallized bars were cracked by the end of the testing, and many exhibited black corrosion products on the bar surfaces. The copper-clad samples were found not to stain or crack, but the cladding cracked during bending.

When Type 304 stainless steel bars were used in both mats, the corrosion rates were approximately 1500 times lower than for the black-bar specimens, with or without a concrete precrack. However, Type 304 bars that were coupled to black-bar cathodes produced moderate to high corrosion currents and were susceptible to localized chloride-induced corrosion. Also, red rust was observed on the precracked concrete samples that had black-bar cathodes. These results showed the uncertainty of using Type 304 with black-bar bottom mats in severe environments.

Type 316 stainless steel bars produced extremely low macrocell corrosion potentials in all test conditions, with corrosion approximately 800 times lower than that for black bars. Unlike the Type 304 bars, the galvanic effects of coupling with black bars were not seen. Visual inspection showed only one sample to have minor corrosion. The investigators concluded that Type 316 stainless steel bars could be considered for structures seeking long design lifetimes of 75 to 100 years.

CORROSION IN SEAWATER

Flint and Cox (1988) investigated the use of Type 316 stainless steel bars exposed to both flowing and stagnant seawater in full immersion and in tidal conditions. For each test sample, three rods were imbedded in two blocks of concrete. The rods were placed vertically with approximately 20 mm, 40 mm, and 72 mm (0.8, 1.6, and 2.9 in) exposed for specimens of length 150 mm, 200 mm, and 250 mm (6.1, 8.2, and 10.2 in), respectively. The concrete blocks, supported by a 6-mm (0.24 in) backing strip, were stacked with a 3-mm (0.12 in) gap between the blocks. This gap was to induce a crevice to study the potential for corrosion of the stainless steel in cracked concrete in seawater. Mild steel bars were also tested for control.

The blocks were installed in May, and after the first summer, the samples were entirely covered with marine growth. After the first year, no corrosion attack was evident in the Type 316 steel bars, but the mild steel bars showed some corrosion. The longer specimens showed more severe corrosion, and the samples in the tidal zone had greater attack than those fully immersed. After seven years, there was more severe corrosion on the mild steel bars with local attack in the gap region having a reducing effect on the tensile strength of the specimen. However, Type 316 steel bars showed only superficial attack. After approximately 12.5 years, only one of the 250-mm-long Type 316 steel bars showed corrosion attack. Corrosion was beginning at the surface of the lower block and continuing down the rebar/concrete interface. The excellent performance of the Type 316 steel bars under these severe crack-simulating crevice conditions was attributed to the alkalinity of the concrete.

EFFECT OF ACID RAIN

There has been considerable investigation into the environmental impact of acid rain on the streams and forests of Pennsylvania. There is very little information, however, on the impact of acid rain on structures such as bridges. This information gap was uncovered in an American Chemical Society publication (Webster et al. 1986) devoted to the degradation of a wide range of materials by acid rain. Acid can attack concrete by dissolution of material from the concrete or by the reaction with compounds resulting in the formation of salts that precipitate within the pores creating mechanical stresses. These forms of attack can affect the physical and chemical well being of the concrete, resulting in a material with compromised strength and a more corrosive environment for the rebar.

The increase in rate of deterioration of reinforced Portland cement concrete in polluted areas has been attributed to acids such as SO_2, NO_4 and HCl. Although it is difficult to determine the precise composition of acid rain, concrete is attacked by all of these acids in a similar manner. The rate of attack varies with the specific acid, but sulfuric acid has been found in the highest level. Therefore, the remainder of the discussion focuses specifically on its reaction with concrete. The dissolution occurs due to the reaction of sulfuric acid with the calcium compounds in the concrete such as calcium carbonate ($CaCO_3$), which produces gypsum, or calcium sulfate ($CaSO_4$). Gypsum has a greater solubility in water and is flushed out. As cement paste is dissolved, the aggregate below is exposed. The underlying lime (calcium hydroxide) in the pore solution then diffuses to the surface and precipitates as $CaCO_3$. As the lime precipitates out, the pore water is left unsaturated, which enables more calcium hydroxide to be dissolved in the pore water. Therefore, lime throughout the structure is diffusing to the surface for reaction and is leached away. This initially results in the surface etching followed by pitting and scaling of the concrete. Acid may also destroy concrete by reacting with the calcium compounds to form soluble salts. In the surface region, these salts are rinsed away by rainwater. Deeper within the concrete, however, the salts accumulate resulting in an increase in volume creating internal stresses. A more conductive path to the rebar for electrochemical reactions is then formed due to the cracking and spalling of the concrete.

The pH and hydrogen ion loading in Pennsylvania have been measured. The normal pH for uncontaminated rainwater is 5.6, slightly acidic from a neutral value of 7 (Schneck et al. 1999). Maps (Figure 6) by the Environmental Resources Research Institute of Pennsylvania State University indicate the hydrogen ion deposition and pH measured by the Pennsylvania Atmospheric Department Monitoring Network. These maps may be useful in determining the impact of acid rain by comparison with the performance of bridges across the state.

Although there has been little investigation into the effect of acid rain on functional structures, there has been a great deal of work done on statues and ancient structures. Livingston (1994) points out that concrete is not a modern material. Structures made of concrete in the Roman and Byzantine periods can be evaluated for long-term degradation. Although some of the starting materials differ, many of the reaction products are identical for ancient concrete and Portland cement concrete. Therefore, by making use of the information gathered in the study of ancient artistic or historic structures, a better understanding of long-term performance may be gained. The transfer of knowledge may also allow us to better learn from past mistakes. For example, the reinforcement in the marble columns in the Parthenon was originally iron sheathed with lead. Repairs made after a 16th century war utilized iron dowels without the lead sheath, resulting in serious spalling. Restoration efforts in the 1970's replaced the iron dowels with titanium dowels expected to resist further corrosion problems.

VII. LIFE-CYCLE COST FACTORS FOR STAINLESS REINFORCEMENT

PROJECT COST

When considering the use of stainless steel reinforcing with its extra initial cost, there should be a defined or potential corrosion problem with an economic consequence. There are a variety of design and other considerations and special circumstances that may adequately justify the use of stainless reinforcement as an added project cost. These include among others:

- Other sections of the bridge that can be expected to provide a 50-year-plus life.
- Low concrete cover situations forced by design/circumstance.
- High volume/pinch-point traffic areas or large-city ingress/egress routes.
- Areas where maintenance/repair is difficult (above ground ramps, narrow highways).
- Areas where alternative routes are not available and facility outage is not easily tolerable.
- Selective areas of high corrosion in a structure (drainage problems etc.).
- Site geography / meteorological exposure based on location /aspect leading to corrosion.
- Selective repair and rehabilitation of specific installation areas (barrier walls, pilings etc.)
- Seismic considerations where there are movable parts to absorb load.

Project cost in this scenario means the cost of a bridge deck, for example, not the total cost of the bridge. Since the typical cost of rebars in a bridge deck is about 4 percent of the cost of the deck when black bars are the reference, a direct substitution of corrosion-resistant stainless steel bars would raise the representative initial project cost about 18 percent. Thus, the effect of the ratio of Type 316LN stainless bar material costs to black bars (5.5 to 1) is markedly reduced when project costs are compared (1.18 to 1). But, direct bar substitution still adds significant cost to the initial project cost.

Moreover, direct bar substitution is often not the optimum design approach to achieving more corrosion resistance. As one example, in a bridge deck with both top and bottom reinforcing bar mats, it may be essential only to provide corrosion-resistant bars in the top mat. This partial bar substitution would somewhat limit the increase in project cost due to corrosion-resistant bars.

However, it also requires more consideration of the galvanic corrosion factors related to using dissimilar steel bars.

Life-Cycle Cost

Life-cycle costing (LCC) is the approach most advocated by the corrosion-resistant-reinforcing bar industries. It is a valid approach; however, the United States' reluctance for widespread adoption of LCC must be overcome so that the expected reduced life-cycle costs of alternative materials can be realized. Life-cycle costing may not alone always justify stainless or stainless-clad products, but there are justifying circumstances. For example, life-cycle costs that include user-delay costs may help to justify use of stainless reinforcing bars in high traffic and limited access areas.

Life-cycle cost factors in all the monetary aspects of a structure to evaluate how expensive it "truly" is. Life-cycle costs include not only the initial material and labor costs, but also the cost and frequency of future repairs and the cost to the public at large of not being able to fully use the structure during repair time. Ideally, if using stainless steel reinforcing can increase the design life of a bridge deck, and/or reduce the frequency of repairs required, then an increase in the initial construction costs may be economically justifiable.

A strong drawback to life-cycle costing is that it requires numerous estimates regarding the future, although computer programs have been written to calculate these life cycle costs from user-provided initial cost data and estimates. Program developers include the stainless-steel-industry organization, Specialty Steel Industry of North America (SSIUS), Lehigh University (Veshosky, Wagaman, et al. 1998), and the U.S. Department of Commerce's National Institute of Standards and Technology (NIST 1999).

The SSIUS program specifically addressed stainless steel. Although the program was written for a DOS environment and, consequently, is no longer much used, it presents a technique for identifying and quantifying all costs, initial and ongoing, associated with a project or installation over a given period. While it is not specific to bridge or highway applications (it was initially developed for pressure vessel applications), it considers projections of future interest and inflation rates, maintenance intervals and costs, and the desired service life while using a "present value" concept. For reinforcing bar material costs, it would assess initial outlay, maintenance and frequency, downtime effects, traffic or revenue losses, repair, replacement, manpower, energy consumption, and recycle costs. Figure 7 shows the equation of summations used in this LCC program, and a summary of an example analysis (made by SSIUS) comparing a stainless steel walkway with one of carbon steel. In this example, stainless steel had an initial material cost exceeding three times that of carbon steel, but the projected 30-year life-cycle cost of the stainless steel walkway was 55 percent of that of the carbon steel walkway.

The Lehigh investigators (Veshosky, Wagaman, et al. 1998) developed software focusing on the analysis of bridge deck life-cycle costs. Based on input from PennDOT, Caltrans, and bridge engineering practitioners, five pre-specified alternative deck designs with reinforcing bars were studied and ranked based on initial costs, owner LCC, and total (initial plus owner) LCC. Their assumptions included an inflation rate and the discount rate of money. The alternatives did not include stainless reinforcing (only epoxy-coated and uncoated carbon steel bars), but the software would allow any bars. This life cycle study showed that decks with uncoated carbon steel rebars, although having the lowest initial cost, had the highest total LCC for a bridge with a 75-year life, regardless of the deck overlay used. This example illustrates the life-cycle-cost benefit of corrosion-resistant reinforcement.

The NIST program (Ehlen 1999a) focuses on concrete bridges. Known as Bridge LCC, this program is designed to run in a Windows ™ environment. It allows evaluations of the cost-effectiveness of alternative construction materials, including reinforcing bars. Its life cycle methodology is based on the ASTM standard for LCC (E917) and a NIST-developed cost classification scheme. The program has been briefly described in a trade journal (Ehlen 1999b). An example was run using the NIST program to compare the life-cycle costs of a bridge deck where epoxy-coated bars are the base condition and 316LN stainless steel bars are a direct-substitution alternative. The bridge deck used is one included as an example case in the program: a 44-foot-wide, 80-foot long rural prestressed concrete I-beam highway bridge designed for HS20-44 loading. The deck is 8.0 inches thick, and uses Class A4 concrete. It is assumed that the entire bridge will be disposed of in 75 years. Figure 8 identifies and tabulates the costs to construct, maintain, and dispose of the deck. (Only the deck was considered in this adaptation of the NIST example.) For the deck with epoxy-coated rebars, the initial rebar cost is $29,260 and the LCC is $301,264.60, excluding the user costs that are incurred as users are stalled or rerouted every 25 years during resurfacing. For the deck with 316LN stainless steel bars, the initial rebar cost is much greater—$107,800—but the LCC is lower—$230,104.60. This is due to two assumptions: (1) no resurfacing with stainless rebars, and (2) salvage value of $0.30/lb with the stainless rebars. Thus, in the example, the initial premium of $78,540 for the stainless rebars resulted, after 75 years, in a life-cycle cost benefit of $71,160 over epoxy-coated rebars. (This example is meant to illustrate how LCC can affect project costs; it does not knowingly represent any actual bridge deck costs.)

Life-cycle-cost software tools for evaluating corrosion protection in concrete are also being developed by the cement and corrosion inhibitor industries. Grace Construction Products (Durning 2000), which manufactures durability admixtures, has DuraModel, ™ a software tool to couple service life prediction with life cycle cost. It determines the time-to-repair for different product, quality, and environmental options, determines the present value of projected repairs, and then yields the present value LCC. Grace is cooperating and helping to fund the development of other software LCC models being developed by the University of Toronto and by the Concrete Corrosion Inhibitor Association (CCIA).

VIII. COMPETING CORROSION-RESISTANT REINFORCING SYSTEMS

Stainless and stainless-clad reinforcing bars, although being evaluated for their improved corrosion resistance and benefits on life-cycle project cost, must compete with other corrosion-resisting reinforcing systems. In general, there are two types of competing systems: competing reinforcing bar systems, and other competing systems that reduce the corrosiveness of the environment, i.e., chloride-resisting cements, or provide electrochemical protection such as cathodic protection (CP) or electrochemical chloride extraction (ECE).

Competitive Reinforcing Bar Systems

Commonly used competitive reinforcing bar systems involve carbon steel bars with corrosion-resistant epoxy or galvanized coatings. Another system involves reinforcing bars that are a fiber-reinforced-polymer composite material. Figure 9a illustrates these bar types. Newer dual-phase steels, that are not stainless, are also being marketed as corrosion-resistant for use in rebar applications. Finally, of course, the stainless and stainless-clad bars must compete with each other. This section addresses some aspects of this competitive-bar barrier.

Epoxy-coated Reinforcing Bars. Next to uncoated carbon-steel bars used with a corrosion-resisting system, epoxy-coated bars are the strongest competition to stainless and stainless-clad bars. In Pennsylvania, epoxy-coated bars are approved in PennDOT material specifications Section 709 – Reinforcement Steel, and Section 1002 – Reinforcement Bars. Section 709.1 (d) provides requirements for epoxy-coated bars and Section 709.3 (a) provides requirements for epoxy-coated steel welded wire fabric. Epoxy-coated bars are similarly approved in AASHTO material specifications, and there are ASTM Specifications for straight and bent-after-coated (A775/A775M-96) and bent-before-coated (A934/A934M-96) epoxy-coated bars. ASTM Specification D3963/D3963M-97 provides fabrication and jobsite requirements for A775 coated bars. Thus, these bars have broad acceptance in specifications.

Epoxy-coated bars also have broad market acceptance, evidenced by their inclusion in ENR's weekly section on construction economics, see Table 2. Only uncoated carbon-steel bars and epoxy-coated bars receive this ENR coverage.

Epoxy-coated bars have been (and still are being) evaluated extensively within the National Cooperative Highway Research Program (NCHRP) and the Canadian Strategic Highway Research Program (C-SHRP) and in projects in several individual states. An impetus behind these studies is that, although epoxy-coated bars have been in use for nearly two decades, there have been incidents of corrosion problems and of premature failures in Florida, New York, and Oregon. Some potential problems are evident in Figure 9. The bent-after-coating bar in Figure 9a exhibits breaks in the coating that permit corrosion to initiate. The cross-section in Figure 9b must be coated or capped to prevent corrosion.

NCHRP Report 370 describes Project 10-37 completed in 1994, which studied the performance of epoxy-coated reinforcing steel in highway bridges. Projects 10-37A and 10-37A(01), which involve laboratory testing, examination of failure mechanisms, and extended exposure monitoring are continuing at Florida Atlantic University. Project 10-37B, completed in 1995, describes a protocol for evaluating bridges with epoxy-coated bars. Project 10-37C, aimed at repair and rehabilitation methods for bridge components with epoxy-coated reinforcement is also continuing by Concorr, Inc. (NCHRP).

The C-SHRP report (Clear 1992) has been perhaps the least favorable towards epoxy-coated reinforcing. The project was initiated to determine the effectiveness and long-term (50 years or more) performance of fusion bonded epoxy coatings in preventing the corrosion of reinforcement in highway structures in Canada-like environments. However, the Executive Summary of the final project report concluded that

> "The state of the art evaluations and the field and laboratory testing suggest that fusion-bonded epoxy coatings will not be effective in providing long-term (50 years or more) corrosion protection to reinforcement in salt-contaminated concrete."

> "The data indicate that the increase in life of epoxy-coated rebar structures over those constructed with uncoated rebar in northern U.S. and Canadian environments (marine and deicing salts) will be in the range of only 3 to 6 years in most instances."

Galvanized Reinforcing Bars. Hot-dipped galvanized reinforcing bars are covered by ASTM Specification A767. Galvanized rebars are achieved by immersing clean, uncontaminated hot-rolled rebars in an 850°F bath of molten zinc. The zinc metallurgically bonds to the bars to form a coating that provides both barrier and cathodic protection to the bars. The barrier is the zinc-iron (or zinc carbonate) layer forming the metallurgical bond. Cathodic protection occurs because iron has an electrochemical potential that is noble to that of zinc. Therefore, in the presence of an electrolyte, the zinc is slowly consumed, while the steel is protected. Thus, cathodic protection continues until all the zinc is consumed.

The corrosion-resistance quality of galvanized bars is significantly affected by the quality of the cleaning process and variations in the galvanizing process. Zinc thickness is a primary factor in determining corrosion resistance and, thus, service life for galvanized rebars. As specified in ASTM A767, the minimum thickness of zinc coating is 5 mils for No. 3 bars and 6 mils for larger-diameter bars.

The American Galvanizers' Association (AGA 1996,1998, 1999) states that galvanized rebars can withstand exposure to chloride ion concentrations at least 4-5 times higher than exposures causing corrosion in black steel reinforcement. Moreover, galvanized reinforcement remains passivated at lower pH values, thus offering more protection against the effects of carbonation of concrete.

McDonald et al. (1996) reported to FHWA, however, that the "long-term durability (of galvanized bars with galvanized cathode bars) could only be guaranteed if the entire structure included galvanized steel. Galvanized bars were not effective when used with black cathode bars." Moreover, "bending galvanized bars significantly reduced the corrosion protection."

Fiber-Reinforced Polymer (FRP) Reinforcing Bars. FRP bars represent a growing corrosion-resistant concrete reinforcement system, including reinforcing bars, dowel bars, and prestressing cables (Clarke 1999, Composites 1999). They have both a number of favorable attributes and a number of negative attributes. While a thorough assessment of FRP bars is outside the scope of the report, a listing of several positive and negative attributes follows:

Positive Attributes

- Both highway and pedestrian bridges have been constructed using FRP prestressing cables and reinforcing bars – both in the United States and in Europe.
- Design guidelines, at least in draft form, exist for FRP reinforcement in the United States (by ACI), Japan, Canada, and Europe.
- FRP bars are highly durable in concrete, although not completely so. Hence, crack widths need less limitation for durability reasons, although aesthetic reasons may govern.
- FRP bars have high tensile strength.
- There is notable research ongoing on FRPs; research on new resins, on various fibers—glass, carbon, and aramid—and even on bendable bars.

Negative Attributes

- Most engineers lack the knowledge to specify the most appropriate combination of fiber and resin.
- The maximum bar diameter being produced is about 32 mm.
- Pultruded bars (the commonest manufacturing method) cannot be bent.
- Glass fiber reinforcement (the lowest cost fiber) has low stiffness, so that deflections will be greater than with equivalent steel rebars.
- FRP reinforcement has high cost, see Table 2. Thus, FRP use needs justification from life cycle costing.
- Fire will be a significant design consideration. The temperature rise at the surface of the bars must stay below the glass transition temperature for the resin, so that composite action does not cease.
- Fume-protection masks are recommended when cutting FRP bars.

Dual-Phase Steels. Two dual-phase steels marketed for use as rebars on the basis of enhanced properties are DFM steel rebars and rebars produced by the TEMPCORE process. For both, a controlled rolling and quenching process is used to produce a microstructure with martensitic characteristics. However, the results and attributes are different.

Dual-phase ferrite martensite or DFM steel was developed by a research team at the University of California-Berkeley (Ashley 1995, Popular Science 1995, Thomas 1998, Trejo et al 2000) with a first principle of being corrosion resistant. The research had support from the US DOT through NCHRP, US DOE, and the US Navy. The steel, which has been called both DFM steel and FERMAR steel in literature, is being marketed by MMFX Steel Corporation in Newport Beach, CA (MMFX 1999).

The claim for DFM rebars is that, when embedded in concrete/saline conditions, they exceed the corrosion resistance of all "conventional" (that is, pearlite containing) reinforcing bars. The bars are processed in regular bar mills, but are quenched to control the cooling rate and to provide a low-carbon martensitic structure. One report indicates that DFM bars with 40 percent martensite had only 1/3 as much mass loss as conventional A615 carbon steel bars after 10 months of accelerated corrosion tests in a decanted cement/chloride solution under anodic polarization of 50 mV.

The developers also claim that DFM bars with yield points of 80 ksi and tensile strengths of 110 ksi can be produced, that the bars have excellent plasticity due to their low yield/tensile ratio, that they have a low Charpy V-notch transition temperature of about –75°C, and that they have good weldability due to their low-carbon composition.

MMFX has reportedly (Blauch 2000) offered to produce a sufficient quantity of DFM bars for PennDOT to evaluate the bars in a small bridge structure.

Tempcore® steel bars (Galvarebar 1999) achieve their structure by an intensive quench as the bars emerge from the final hot rolling sequence. The quench produces a hardened martensitic layer. As the bars air cool, this layer is tempered by the internal heat of the core. At conclusion, the bar has a hardened tempered martensite layer, a ferrite-pearlite core, and an intermediate bainite-ferrite layer. The martensite layer has high compressive residual stresses, which enhances fatigue resistance. In fact, it is promoted for its fatigue resistance (Zheng and Abel, 1999) and not for its corrosion resistance. In this regard, one description of Tempcore bars describes them as being highly zinc-coatable. Tempcore steel bars are produced in Europe and in Australia.

Electrochemical Corrosion Protection

It is unclear whether the need will exist for electrochemical corrosion protection with the use of stainless reinforcement. Although proponents (McGurn 1998) of stainless steel state cathodic protection will not be necessary and life expectancy could achieve 100 years, the use of electrochemical treatment of the concrete, i.e., electrochemical realkalization and electrochemical chloride extraction, may be beneficial. As discussed above, this approach is to control the environment to mediate corrosion concerns. Realkalization is the process, as described briefly below, of increasing the pH of the concrete, where chloride extraction focuses on the removal of the insidious chloride ion. A state of the art report on these methods (Mietz 1998) provided the information found in the summary that follows.

Each method is addressed in the following paragraphs, but the Mietz report concludes that neither technique should be considered in areas where the corrosion is due to insufficient concrete cover or inferior concrete quality. These methods should also be avoided in tensioned structures due to the production of hydrogen by the reduction reaction at the rebar, which is free to dissolve into the reinforcement increasing the possibility of hydrogen embrittlement. The authors note there is much debate over this issue. Some feel pre-stressed steel members in ducts are adequately shielded from the applied current, but as the consequences could have significant structural impact, this requires further investigation. Two other potential side effects are the alkali-silica reaction (ASR) and the destruction of the bond between the reinforcement and the concrete. ASR occurs when the excess hydroxide ions react with siliceous aggregate forming a gel that can swell. Although it is believed that a lithium hydroxide or lithium borate electrolyte may prevent this reaction in situations where reactive silica is present, this requires further investigation. The pull out strength of reinforcement has been seen to decrease with electrochemical polarization. Although the mechanism is not clear, it is believed compositional changes in the hardened cement surrounding the rebar may play a role. Another possibility is an increase in pressure at the interface due to the formation of hydrogen gas unable to diffuse quickly out of the concrete. It is clear these side effects need further investigation.

Electrochemical Realkalization is performed with the goal of returning the concrete to its high pH after it has been subjected to carbonation. This is accomplished in the following manner. An anode is placed on the surface of the concrete in an alkaline electrolyte such as sodium carbonate or lithium hydroxide. It is reported that sodium ions that diffuse to the cathode may have some carbon dioxide trapping properties that may slow down the reduction in alkalinity after the treatment. The rebar as the cathode is connected to the surface anode and a direct current is applied. At the reinforcement, hydroxide ions are produced by the reduction of water. At the surface anode, (if the anode is inert), water or hydroxide is oxidized to form oxygen and hydrogen ions. If the anode is active, the oxidation of metal to its ions must be considered to be the surface anodic reaction. These reactions result in the increase in pH at the surface of the reinforcement due to production of hydroxide by the cathodic reaction.

The depth of realkalization measured from the reinforcement was found to be dependent on the magnitude of the current density and the duration of its application. The realkalization measured from the surface, however, was dependent of the duration of application, but not on the magnitude of the current applied. This would be expected since the production of the hydroxide ions at the rebar is due to the applied current forcing the electrochemical reaction, whereas the surface realkalization is due to the absorption and diffusion of ions from the electrolyte at the surface.

As the measure of the pH is fairly insensitive once the pH reaches values greater than 9.5, polarization measurements were performed to evaluate the effectiveness of the realkalization process. The current density values for fresh, carbonated, and realkalized samples were compared when potentiostatically polarized. The fresh samples showed negligible current as would be expected for a passive surface. The samples that had undergone three and five days of realkalization showed considerable dissolution current, even though these samples had passed the phenolphthalein test indicating high pH. Only the sample that had been realkalized for seven days showed true passive behavior. Mietz' report suggests that the measurement of the anodic current may be applied in practice as a performance criterion during the realkalization process to replace the phenolphthalein test found to be an ineffective measure of passive nature of the reinforcement.

The Mietz report concludes that although open questions remain, realkalization may be of interest in concrete structures where weight cannot be increased or is undesirable.

Electrochemical Chloride Extraction (ECE). (As noted earlier, ECE is the topic of another project within the Transportation Materials Partnership under the direction of Dr. Sibel Pamukcu. (Pamukcu 1999)) ECE is also performed by application of a current across the anode in an electrolyte on the surface of the concrete and the reinforcement cathode. The electrolyte can be saturated calcium hydroxide, sodium borate, sodium hydroxide or tap water. When alkaline solutions are used, the hydroxide ions are oxidized resulting in a drop in pH. With a neutral solution such as water, oxidation results in the formation of oxygen and hydrogen ions, or the acidification of the electrolyte. Not only will the chloride ions react with the hydrogen ions to form hydrochloric acid causing potential damage to the top layers of concrete, but chloride ions can react at the anode to form a chlorine toxic gas. The use of alkaline electrolytes may eliminate the acidification and formation of chlorine gas. Another possible solution to the formation of Cl_2 is the use of copper as the anode, which oxidizes and forms copper chloride.

ECE was investigated by the Strategic Highway Research Program resulting in recommendations for application of this method. The anode is recommended to be an activated titanium grid with an alkaline electrolyte capable of buffering and preventing the formation of chlorine gas. Lithium borate solutions were found to provide adequate buffer and also counteract the ASR through the formation of a non-expansive gel. A current density ranging from 1 to 5 A/m^2 is recommended with a maximum voltage of 50V for safety reasons.

The methods briefly described above hold promise for prolonging or reforming the passive film on the reinforcement due to controlling the environment. Most of the side effects enumerated can be avoided with careful design of the application. There appears to be many open questions, however, including recommendations regarding deterioration levels that are too great to see improvement with these techniques.

Other Competing Corrosion-Resisting Systems

As corrosion is the reaction of a material with its environment, corrosion prevention can address not only the material's resistance to corrosion, but also the corrosiveness of the environment. One key barrier to the use of stainless steel as reinforcement may be a decrease in the aggressiveness of the environment, i.e. the concrete. Concrete is highly alkaline in nature, which promotes the formation of a passive film on steel rebar. The use of deicing salts, however, allows the penetration of chloride ions, "passivity destroyers," resulting in the breakdown of the protective oxide and corrosion of the rebar. The corrosion products have a greater volume, creating stresses that lead to cracking and eventual spalling of the concrete. The elimination of the chloride at the rebar surface could minimize the corrosive environment and, thus, minimize the benefit of stainless steel reinforcing. Two approaches are discussed below, the elimination of deicing salts and an improvement in the quality of concrete and concrete practices.

Deicing Salt Practices. A competitive barrier to using stainless steel rebar in Pennsylvania may be the renewed interest in calcium magnesium acetate (CMA) for use as a deicing or anti-icing material (Ormsby 1999). It has long been known that the use of deicing salts, primarily sodium chloride and calcium chloride, has a detrimental effect on the corrosion of concrete structures. The corrosive impact of salt on the nation's highways led to the search for alternative candidate materials in the 1970s. CMA and methanol were proposed as alternatives, but methanol was eliminated as a candidate due to its flammability. Although the desirable properties of CMA were sufficient to justify restricted use and commercial production, the cost of CMA prevented widespread use.

Ormsby highlights a Federal Highway Administration (FHWA 2000) investigation reporting two methods for producing CMA from waste products. Bioengineering Resources Inc. (BRI), in a process consisting of gasification and fermentation, used municipal refuse and sewage sludge. Ohio State University (OSU) developed a fermentation process using cheese whey waste products. Both processes result in the formation of acetic acid that is then reacted with dolomitic lime to form CMA. OSU produced a crude product by reacting dolomitic lime with an acetic acid-rich "broth" and a more pure product by first extruding the acetic acid from the broth and then reacting it with dolomitic lime. Characterization and chemical analysis were performed to compare the three production methods by scanning electron microscopy (SEM) and energy-dispersive x-ray spectroscopy (EDS), respectively. The SEM results showed well-defined dense pellets (~ 3mm dia.) for a commercial Cryotech CMA^{TM} product, where the BRI and OSU samples were smaller, irregular particles. Chemical analyses determined that the BRI and Cryotech samples were relatively pure. The OSU samples, however, showed considerable contamination of sulfur and chlorine in both crude and refined samples and of sodium in the crude broth sample. The effect of the purity of the CMA on the deicing properties is unclear as Ormsby reports that the physical properties and performance of the BRI CMA, as well as those of the crude and refined OSU products, compared well with commercially available Cryotech CMA^{TM}.

Although the focus of the Ormsby report was the new processing techniques, the influence of CMA on corrosion was also discussed, directly addressing the question of whether the addition of CMA would increase the corrosion of a structure with previous salt contamination. Ormsby summarized an unpublished study by Peart and Jacoby in which mortar samples with rebars were prepared with sodium chloride and CMA admixtures. These samples were then immersed in CMA and sodium chloride solutions. Electrochemical techniques were utilized to evaluate the corrosion after 500 days of immersion. The corrosion rate determined from measurement of the corrosion current for sodium chloride-contaminated samples immersed in CMA was an order of magnitude less than that for the samples immersed in sodium chloride solution. Rebars recovered from immersion samples were also investigated. The samples prepared with sodium chloride admixtures showed no significant corrosion when immersed in the CMA solution, but exhibited severe corrosion when immersed in sodium chloride solution. This indicated that exposure of structures with Cl^- contamination to CMA would not be expected to experience increased corrosion. Mortar-rebar samples with and without CMA admixtures were also immersed in sodium chloride solution. The CMA-containing samples fared much better than the control sample. Thus, CMA may also provide some protection from corrosion. This agrees with the finding from inhibitor studies in the late 1970s. Mortar-rebar samples were also immersed in solutions with inhibitors. The electrochemical testing on these samples showed excellent inhibitor properties for the CMA.

Ormsby also reports that CMA has nil environmental impact, with no negative impact on wildlife, water sources, or vegetation. Product literature on the Cryotech Deicing Technology web site (Cryotech 1998) addresses the environmental issues of biodegradability and aquatic toxicity. The literature compares the environmental impact with sodium chloride on the soil, vegetation, groundwater, surface water, aquatic life, humans/mammalians, water treatment, and air pollution, and indicates minimal impact of the commercially available CMA. The combination of a positive environmental impact, effective de-icing and anti-icing properties demonstrated since the 1970s, and new cheaper production methods, led to a DOT news release in December 1999 (U.S. DOT 1999), which states: "Although salt is less expensive, CMA has no significant health or environmental concerns. It is not corrosive to vehicles and not harmful to concrete, structural steel, vegetation, fish or other aquatic life." And further, "deicing tests have shown that the whey-based product has an equal or slightly better ice penetration rate than that of commercial CMA." The news release also states that CMA produced from cheese whey is less than 30 percent of the market price for commercial CMA. Based on these results, CMA should be a highly competitive corrosion-resistant system.

Concrete Practices. The type of concrete and suitability of concrete specifications could play a role in the ultimate performance of stainless steel rebars. There may be a tendency to relax the requirements for the concrete with stainless reinforcement, which would increase the chloride ingress producing a more corrosive environment. On the other hand, a current push toward lower permeability concrete may make the environment for any chosen rebar less severe.

High-Performance Concrete (HPC) refers to concrete capable of meeting specific uniformity and performance properties that are not routinely met by normal procedure using conventional materials and traditional mixing, curing, and placing practices (Zia et al. 1997). This leaves a great deal of variability in the constituents in HPC. Therefore, generalization of the performance of rebar in HPC is not possible. A recent report (Tikalsky 2000) suggesting grade identification with limits on properties such as chloride penetration may be significant in predicting performance.

The importance of quality concrete has been recognized and has been the focus of several studies. In a review of corrosion protection for concrete bridges (Virmani et al. 1998), the variables affecting the concrete quality and the results of several studies are discussed. The corrosion rate and the corrosion potential were used as measures of quality. The type of cement, mineral admixture, coarse and fine aggregate, as well as water-cement ratio, air content and exposure environment were varied. The results determined a significant dependence of the corrosion rate on the concrete mix components. The greatest factors were the cement type, mineral admixture, fine aggregate and water-cement ratio, where the coarse aggregate and air content had less of an influence. The most significant improvement in resistance to deterioration was found to be quartz aggregate with a Type 1 cement and silica fume admixture. Although the authors note that blended cements may result in a decrease in alkalinity in the concrete, this may be offset by the reduction in permeability and conductivity. Virmani's review also notes that the effect of the chloride concentration is dependent on the humidity and temperature of the environment.

Even with the proper selection of constituents, concrete may crack if curing practices are not strictly followed, thus allowing the corrosive species direct access to the reinforcement. Properly cured low-permeability concrete may also eventually crack from conditions such as freeze-thaw cycles. To address crack formation during curing, Kiss and Hill (2000) proposed as an alternative the use of polymer fibers. To minimize unrestrained plastic and drying shrinkage as a cause of cracking in newly placed concrete, the suggestion was to add polymer fibers (about 1.5 lb. per cu. yd. of concrete). The fibers would suppress plastic shrinkage cracking, reduce the segregation of the mix constituents, and increase the toughness of the concrete.

Another commonly used practice to both delay the onset of corrosion and to reduce the rate of corrosion is to roller-impregnate the concrete surface with a penetrating corrosion inhibitor (Sika

Ferrogard 903 is one such product), which protects the rebars by forming a protective layer on their surface. FHWA (2000) discusses a number of inhibitors. With every practice, however, maximum structural integrity will always depend on the ability of the rebars to resist corrosion. This is the premise for using stainless steel rebars.

IX. SUMMARY

Stainless steel reinforcing bars are demonstrating excellent resistance to corrosion both in laboratory studies and in field installations that have been implemented. Stainless-clad reinforcing bars are also finding acceptance, although these are largely still in trial evaluations. Field installations or trials are underway or are beginning in about 30 states for either stainless or stainless-clad bars, both rebars and dowels.

Neither stainless nor stainless-clad reinforcing bars have adequate representation in specifications and standards, although progress is being made. The major impediment to using stainless steel is its initial cost. However, solid stainless steel bars can provide cost savings as compared to black bars based on life-cycle costs, and stainless-clad steel bars are only approximately twice the cost as black bars, potentially leading to even more life-cycle savings.

Although there are a number of competitive anti-corrosion systems, including other types of reinforcement and chemical corrosion-resistant systems, the number of installed examples of stainless and stainless-clad rebars should continue to increase, based on the benefits that stainless and stainless-clad steel reinforcing can provide.

X. REFERENCES

Section I - Introduction

Basham, K. "Choices in Corrosion-Resistant Rebar." *Concrete Construction* October 1999, pp. 27-33.

Bower, J. E., L. E. Friedersdorf, A. I. Juda, A. R. Marder, and B. H. Neuhart. "Application of Stainless and Stainless-Clad Steel Reinforcing Bars in Highway Construction – Status Report: Current Applications and Research Review." ATLSS Engineering Research Center, Lehigh University, Bethlehem, PA, November 30, 1999.

Bower, J. E., L. E. Friedersdorf, B. H. Neuhart, and A. R. Marder. "Application of Stainless and Stainless-Clad Steel Reinforcing Bars in Highway Construction – Status Report 2: Barriers and Issues Affecting Application." ATLSS Engineering Research Center, Lehigh University, Bethlehem, PA, May 31, 2000.

Concrete Society. "Guidance on the Use of Stainless Steel Reinforcement." Technical Report TR-51, The Concrete Society, Berkshire, UK, 1998, p. 7-9.

FHWA. See McDonald et al (1996).

FHWA. "Materials and Methods for Corrosion Control of Reinforced and Prestressed Concrete Structures in New Construction." Office of Infrastructure R&D, Report No. FHWA-RD-00-081, 2000.

Gedge, G. "The Use of Stainless Steel Reinforcement in Concrete." *Concrete* May 2000, pp. 12-14.

Gedge, G. and J. Martin. "Investigation of Initial & Life-Cycle Costs of Using Stainless Steel Reinforcement in Highway Structures." 9th International Conference on Structural Faults and Repair, Edinburgh, UK, July 4-6, 2001.

McDonald, D. B., D. W. Pfeifer, and G. T. Blake. *The Corrosion Performance of Inorganic-, Ceramic-, and Metallic-Clad Reinforcing Bars and Solid Metallic Reinforcing Bars in Accelerated Screening Tests.* Report No. FHWA-RD-96-085, U.S. Department of Transportation, Federal Highway Administration, McLean, VA, October 1996, 112 pp.

Neuhart, B. H. "Use of Stainless Steels in Reinforced Concrete Structures – Status 1998." International Conference on Corrosion and Rehabilitation of Reinforced Concrete Structures (ICCRRCS), Orlando, FL, December 7-11, 1998.

Neuhart, B. and J. Martin. *Stainless Steel Reinforcement in Bridge Construction – Status 2000.* Paper No. IBC-00-18, 17th Annual International Bridge Conference, Engineers' Society of Western Pennsylvania, Pittsburgh, PA, June 12-14, 2000.

OTA. "Construction and Materials Research and Development for the Nation's Public Works, Chapter 7, Recent Materials Developments-Anticorrosion Methods." Office of Technology Assessment Staff Paper (1987).

Pamukcu, S., H. Moo-Young, and D. Burleigh. "*Feasibility of the Use of Cathodic Protection and Electro-Chloride Extraction Technology for Structures in Pennsylvania.*" Work Order No. 5, Research Program 359631, Transportation Materials Partnership, Pennsylvania Department of Transportation, Harrisburg, PA (1999).

Seminar Reprints – "Solving Corrosion Problems in Concrete." Chicago, September 27-29, 1982. Sponsored by Federal Highway Administration.

- Clear, K. C. and Y. P. Virmani. "Research Update: Methods and Materials."
- Hartt, W. H. and R. P. Brown. "Cathodic Protection of Steel in Concrete."
- Hooker, W.H., B. Husock, and R. M. Wilson. "Overview of the Rebar Corrosion Problem."
- Locke, C. E. "Mechanism of Corrosion of Steel in Concrete."
- Nishimura, G. "Hot Dip Galvanizing for Reinforcing Steel."
- Perenchio, W. F. and D. W. Pfeifer. "Coatings, Penetrants and Specialty Concrete Overlays for Concrete Surfaces."
- Whitting, D. "Corrosion Control – Concrete Design and Construction Practices."

TRB. *Emerging Concepts and Products for Highway Systems, Annual Progress Report 2,* Transportation Research Board, National Academy of Engineering, Washington, DC (1995).

- NCHRP-IDEA Project 3, Sagues, A. A. and R. G. Powers. *Development of Guidelines for Low-Cost Sprayed-Zinc Galvanic Anode for Control of Corrosion of Reinforcing Steel in Marine Bridge Substructures*, pp 11-12.
- NCHRP-IDEA Project 9, Darwin, D., C. E. Locke, Jr., M. R. Senecal, J. L. Smith, and S. M. Schwensen. *Corrosion-Resistant Steel Reinforcing Bars*, pp 37-43.
- NCHRP-IDEA Project 10, Sanjurjo, A., K. Lau, D. Lowe, D., P. Jayaweera, and G. Krishnan. *Metallic Coating for Corrosion Protection of Steel Rebars*, pp 44-51.
- NCHRP-IDEA Project 19, Stein, D., F. Lu, K. Rajeshwar, and P. B. Aswath. *Aluminum Bronze Alloy for Corrosion-Resistant Rebar,* pp 81-82.

Tullmin, M., F. N. Smith, and P. Gu. *The Inclusion of Stainless Steel Rebars into a Major Highway – The Information Super Highway*, ICCRRCS, Orlando, FL, December 7-11, 1998.

www.stainless-rebar.org *Stainless Steel Rebar International Bulletin.* Tullmin Consulting, Kingston, OT (1999).

Section II – Types and Properties

Chute, D. O., and B. W. Christ. *The National Shipbuilding Research Program Welding Fume Study.* Paper No. 14. 2000 Ship Production Symposium, The Society of Naval Architects and Marine Engineers, Williamsburg, VA, August 24-25, 2000. 6pp.

Fisher, J. W. *Structural Integrity: Fatigue Resistance.* ONR Grant N00014-99-0887, Nonmagnetic Stainless Steel Double Hull Ship Construction, ATLSS Engineering Research Center, Lehigh University, Bethlehem, PA (2000).

Johannson, R. E. and H. L. Groth. *Fatigue Data for Stainless Steels.* Avesta AB, Research and Development, Avesta, Sweden, Proceedings of a Swedish Conference on "Mechanical Properties of Stainless Steels," October 1990.

Lamb, S. (Technical Editor). *Handbook of Stainless Steels & Nickel Alloys.* Casti Publishing Inc., Edmonton, Alberta, ISBN 1-894038-34-7 (1999).

McGurn, J. F. *Stainless Steel Reinforcing Bars in Concrete.* ICCRRCS, Orlando, FL, December 7-11, 1998.

NSRP. *Welding Fume Study Final Report,* NSRP 0525, The National Shipbuilding Research Program, Naval Surface Warfare Center Carderock Division in cooperation with Halter Marine Group, Inc, 1999.

Rolled Alloys. *AL-6XN Alloy: Physical, Mechanical and Corrosion Properties*, Bulletin 210, Rolled Alloys, Temperance, MI, August 19, 1997 Revision.

SSINA. *Design Guidelines for the Selection and Use of Stainless Steel,* Publication 5-98-20, Specialty Steel Industry of North America, Washington, DC, www.ssina.com (1998).

Section III – Availability and Pricing

Abbott, C. J. *Stainless Steel: The Total Solution for Extended Design Life in Corrosion Free Concrete Structures.* Paper and Company Product Catalog, Stainless Steel Reinforcement Limited, Chessington, England (1996).

Neuhart, B. H. Letter to D. Rettner, Minnesota DOT Materials Research. "Cost Estimates for Stainless Steel Dowel Tubes."(2000).

SSINA. *Stainless Steel for Structural Applications: with Directory of Structural Producers.* Publication 9-99-5000, Specialty Steel Institute of North America, Washington, DC, 1999, www.snina.com.

Stelax. *NUOVINOX Update,* June Edition, Stelax Industries Ltd, Neath, West Glamorgan SA11 2JX, U.K., 1999a, www.stelax.com

Section IV – Standards

AWS. *Structural Welding Code—Reinforcing Steel.* Fifth Edition, ANSI/AWS Standard D1.4-98, American Welding Society, Miami, FL, 1998.

BSI. *BS-6744 – British Standard Specification for Austenitic Steel Bars for the Reinforcement of Concrete,* British Standard Institution, London, England, 1986.

Concrete Society. "Guidance on the Use of Stainless Steel Reinforcement." Technical Report TR-51, The Concrete Society, Berkshire, UK, 1998, pp. 7-9.

Michigan. *Special Provision for Reinforcement, Stainless Steel,* C&T:Appr:RDT: MF 06-19-99, 3 pp (1999).

Milne, D. UK Highways Agency Letter to G. Harding (Harding@detr.gsi.gov.uk), forwarded to J.E. Bower, May 23, 2000.

Pianca, F. "DRAFT, January 2000, Non Standard Special Provision for Reinforcing Stainless Steel Bar and Stainless Steel Mechanical Connectors," Materials Engineering and Research Office – Concrete Section, Ontario Ministry of Transportation, Downsview, ONT (2000a).

Pianca, F. Phone conversation with J.E. Bower, ATLSS, October 26 (2000b).

Powers, R. (Florida DOT), Phone Conversation with J.E. Bower (ATLSS), May 18, 2000.

REVAL. "Stainless Steel Reinforcing Bars." Product Literature, Acciaierie Valbruna, Vicenza, Italy, 6 pp. (Available through Tell Steel, ph: 800-734-8355).

Stelax. *Standard Specification for Deformed and Plain Stainless Steel Clad Carbon Steel Bars for Concrete Reinforcement [Metric],* STLX995-99 (1999b). (Also included as Enclosure 10 in Stelax (1999a)

Section V – Trials and Performance

Anonymous Letter to D. Bischoff – Wisconsin DOT , "Re: Dowel Bar Tests." August 26, 1997.

Beck, S. Michigan Department of Transportation. E-mail to A.I. Juda, July 12, 1999.

Cable, J. K. and L. L. McDaniel. "Demonstration and Field Evaluation of Alternative Portland Cement Concrete Pavement Reinforcement Materials." Iowa State University Department of Civil and Construction Engineering Final Report for Iowa DOT Project HR-1069, FHWA W.O. #DTFH71-97-TE030-IA-48, August 1998.

CERF. "Alternative Material Dowel Bars for Rigid Pavement Joints." HITEC Evaluations, www.cerf.org/hitec/eval/ongoing/dowel.htm, January 2000. Also see "Noncorrosive Dowel Bars to be Evaluated." *Civil Engineering* September 1999, p. 26.

Clemena, G. G. Virginia Transportation Research Council. E-mails to A.I. Juda, June 24 and 29, 1999.

Crovetti, J. A. "Cost Effective Concrete Pavement Cross Sections – Interim Report." Marquette University Center for Highway and Traffic Engineering Report No. WI/SPR 12-99, Wisconsin DOT Project WI/SPR 95-03, August 1999.

Cryer, C. B. Oregon DOT. E-mails to A.I. Juda, June 21 & 23, 1999.

Gawedzinski, M. J. Illinois DOT. E-mails to A.I. Juda, June 29, 30 and July 7, 1999.

Hope, B. B., A. K. C. Ip, and F. Pianca. *"Application of Stainless Steel Reinforcement for Highway Bridges in Ontario." Proceedings of the Second International Conference on Concrete Under Severe Conditions*, Tromsø, Norway, June 1998, pp. 1884-1892.

Kahl, S. Michigan DOT. E-mail to A.I. Juda, July 13, 1999.

Koon, T.E., E-mails to J. E. Bower, November 7 and 14, 2000.

Knudsen, A. and T. Skovsgaard. "Ahead of its Peers." *Concrete Engineering International* August/September 1999, pp. 58-61.

Loftus, M. New York State Thruway Authority. E-mail to A.I. Juda, July 14, 1999.

McGinnis, J. Maine DOT Laboratory Test Report and Special Provision Section 503 Reinforcing Steel (Stainless Steel Coated Reinforcing Bar), e-mails and faxes to A.I. Juda, July 1 and 8, 1999.

Mends, N., E-mails to J.E. Bower, November 14 and 17, 2000.

Mumber, J., R. Krishnagiri, R. Halczli. "New Jersey's First Steel Monocell Box Girder." Paper No. IBC-99-35, 16th Annual International Bridge Conference, Engineers' Society of Western Pennsylvania, Pittsburgh, PA, June 15, 1999, pp. 201-208.

Powers, R.G. Florida DOT. E-mail to A.I. Juda, July 26, 1999.

Purvis, R.L., E-mails to J.E. Bower, November 8 and 13, 2000.

Rettner, D. Minnesota DOT. E-mails to A.I. Juda, June 22 and July 7, 1999.

Rubeiz, C. Memo sheets to High Performance Steel Steering Committee with IBRC – FY2000 Award Selections, January 20, 2000.

Sarcinella, R. Texas DOT. E-mail to A.I. Juda, July 29, 1999.

Snyder, G. Indiana DOT. E-mails to A.I. Juda, June 23 and 29, and July 7, 1999.

Weisner, J. P. Maryland State Highway Administration. E-mail to A.I. Juda, July 16, 1999.

WJE. "Investigation of Bridge Containing Epoxy Coated and Solid Stainless Steel Reinforcing I-696 over Lenox Road Near I-75, Ferndale, Michigan," Document No. 920970, Wiss Janney Elstner Associates, Northbrook, IL, September 30, 1993.

www.stainless-rebar.org *Stainless Steel Rebar International Bulletin.* Tullmin Consulting, Kingston, OT, 1999.

Section VI – Corrosion Resistance

Bertolini, L., F. Bolzoni, T. Pastore, and P. Pedeferri. *Comportomento di Acciai Inossidabili in Calcestruzzo in Presenza di Clorri,* L'industria Italiana del Cemento, 681, 651-656, 1993.

Bertolini, L., F. Bolzoni, T. Pastore, and P. Pedeferri. *Stainless Steel Behavior in Simulated Concrete Pore Solution,* British Corrosion J., 31, 218-222 (1996).

Bertolini, L., M. Gastaldi, M. Pedeferri, P. Pedeferri, and T. Pastore. *Effects of Galvanic Coupling between Carbon Steel and Stainless Reinforcement in Concrete,* ICCRRCS, Orlando FL, December 7-11, 1998.

ENR. *News in Brief – Japan's NKK Wins Order for Three Gorges Steel*, August 9, 1999, p. 25.

Fisher, J. W. *Structural Integrity: Fatigue Resistance*, ONR Grant N00014-99-0887, Nonmagnetic Stainless Steel Double Hull Ship Construction, ATLSS Engineering Research Center, Lehigh University, Bethlehem, PA, 2000.

FHWA. "Materials and Methods for Corrosion Control of Reinforced and Prestressed Concrete Structures in New Construction," Office of Infrastructure R&D, Report No. FHWA-RD-00-081 (2000).

Flint, G. N. and R. N. Cox. "The Resistance of Stainless Steel Partly Embedded in Concrete to Corrosion by Seawater." *Magazine of Concrete Research* 40 13-27 (1988).

Hanley, B., T. Coverdale, M. Miltenberger, and C. Nmai. "Electrochemical Compatibility in Concrete Repair." *Concrete Repair Bulletin* May/June 1998, pp. 12-15.

Johannson, R. E. and H. L. Groth. "Fatigue Data for Stainless Steels," Avesta AB, Research and Development, Avesta, Sweden, *Proceedings of a Swedish Conference on Mechanical Properties of Stainless Steels,* October 1990.

Knudsen, A., Jensen, F.M., Klinghoffer, O. and Skovsgaard, T. (1998). *Cost-effective Enhancement of Durability of Concrete Structures by Intelligent Use of Stainless Steel Reinforcement*, ICCRRCS, Orlando FL, December 7-11.

Livingston, R. A. "Transferring Technology from Conservation Science to Infrastructure Renewal." http://www.tfhrc.gov/pubrds/summer94/p94su18.htm.

McDonald, D. B., M. R. Sherman, D. W. Pfeifer, and Y. P. Virmani, Y.P. (1995). "Stainless Steel Reinforcing as Corrosion Protection." *Concrete International* 17:5 (May 1995) pp. 65-70.

McDonald, D. B., D. W. Pfeifer, and G. T. Blake. *The Corrosion Performance of Inorganic-Ceramic-, and Metallic-Clad Reinforcing Bars and Solid Metallic Reinforcing Bars in Accelerated Screening Tests.* Report No. FHWA-RD-96-085, Federal Highway Administration, McLean, VA, October 1996, 112 pp.

McDonald, D. B., D. W. Pfeifer, and M. R. Sherman. *Corrosion Evaluation of Epoxy-Coated, Metallic-Clad and Solid Metallic Reinforcing Bars in Concrete,* Report No. FHWA-RD-98-153, Federal Highway Administration, McLean VA, December, 137 pp. (1998a).

McDonald, D. D. W. Pfeifer, and P. Virmani. *Corrosion Resistant Reinforcing Bars: Findings of a 5-year FHWA Study*, ICCRRCS, Orlando, FL, December 7-11 (1998b).

Nurnberger, U., W. Beul, and G. Onuseit. *"Corrosion Behavior of Welded Stainless Reinforced Steel in Concrete." Otto-Graf Journal* FMPA BW Stuttgart 4 pp. 225-259 (1993).

Nurnberger, U., Ed. (1996). *Stainless Steel in Concrete – State of the Art Report.* Cambridge, UK: The Institute of Materials, 1996. 30 pp., ISBN 1 86125 008 8.

Pastore, T. and P. Pedeferri. *"Corrosion Behavior of Duplex Stainless Steel in Chloride Contaminated Concrete." Proceedings of the International Conference on Stainless Steel* Vol. 1, ISIJ, Chiba, p 351 (1991).

Pastore, T., P. Pedeferri, L. Bertolini, F. Bolzoni, and A. Cigada. "Electrochemical Study on the Use of Duplex Stainless Steel in Concrete." *Proceedings Duplex Stainless Steels* 91, Vol. 2, Beaune Borgogne, France, 28-30 October, pp. 905-913.

Rasheeduzzafar, Dakhil, M. A. Bader, and M. M. Khan. "*Performance of Corrosion Resisting Steels in Chloride-Bearing Concrete.*" *ACI Materials Journal* September-October 1992, pp. 439-448.

Schiessl, P., Ed. *Corrosion of Steel in Concrete*. Report of the Technical Committee 60-CSC RILEM, New York, NY: Chapman and Hall, 1988. Pp 25-46.

Schneck, M., W. E. Sharpe, and J. R. Drohan. *Acid Rain, The Pennsylvania Connection*, The Pennsylvania State University (1999).

Sedriks, A. J. *Corrosion of Stainless Steels, 2nd Edition*. NY: Wiley-Interscience Publication, 1996.

Smith, L. M. and M. Celant, M. *Practical Handbook of Cladding Technology*. Bringas, J.E., Exec. Ed. Edmonton, Alberta: CASTI Publishing, 1998. ISBN 1-894038-19-3, 262 pp.

Sorensen, B., P. B. Jensen, and E. Maahn. "The Corrosion Properties of Stainless Steel Reinforcement." *Corrosion of Reinforcement in Concrete.* C.L. Page, K.W.J. Treadaway, P.B. Bamforth, eds; Elsevier Applied Science, 1990. Pp.601-610.

Treadaway, K.W. J., R. N. Cox, and B. L. Brown. "Durability of Corrosion Resistant Steels in Concrete." *Proceedings of the Institute of Civil Engineers, Part 1* 86, 1989, 305-331.

Webster, R. P., and L. E. Dudacka. "Effects of Acid Deposition on Portland Cement Concrete." Ch. 16 of *Materials Degradation Caused by Acid Rain.* Baboian, R., Ed.. Washington, DC: American Chemical Society, 1986. Pp. 239-249.

Zoob, A.B., P. J. Le Claire, and D. W. Pfeifer. *Corrosion Protection Tests on Reinforced Concrete with Solid Stainless Steel Reinforcing Bars for Joslyn Stainless Steels.* Northbrook, IL: Wiss, Janney, Elstner Associates, Inc., 1985.

<u>Section VII – Life-Cycle Cost</u>

Durning, T.A. "Durability Models." *Structural Engineering* May 2000, pp. 24-25.

Ehlen, M. A. "Bridge LCC 1.0 Users Manual and Software CD." Report NISTIR 6298, National Institute of Standards and Technology, Office of Applied Economics, Gaithersburg, MD, April 30 (1999a)

Ehlen, M. A. "Agencies Gain a Bridge Lifecycle Assessment Tool." *Bridge Builder Magazine* February-March (1999b), pp. 43-45.

NIST. *Bridge LCC Version 1.0, Software for Preliminary Bridge Design,* Software and Users Manual Report No. NISTIR 61-98, National Institute of Standards and Technology Building and Fire Research Laboratory, Gaithersburg, MD, April 30, 1999.

SSIUS. "Life Cycle Costing for Stainless Steel: (a) Introduction Brochure, (b) User's Manual/Version 2.0, (c) 3 ½-in. Diskette." Specialty Steel Industry of the United States, Washington, DC, 1990.

Veshosky, D., S. J. Wagaman, J. R. Romano, J. L. Wilson, and C. R. Beidleman. "Software for Analyzing Bridge Deck Life-Cycle Costs." *Proceedings of the International Bridge Conference,* Paper IBC-98-12, pp. 83-87, Pittsburgh, PA, June 1998.

<u>Section VIII – Competing Systems</u>

AGA. "Galvanizing for Corrosion Protection: A Specifier's Guide to Reinforcing Steel." American Galvanizers Association, Aurora, CO, 1996.

AGA. "Rebar: A Processing and Inspection Guide for Quality Hot Dip Galvanized Reinforcing Steel," American Galvanizers Association, Aurora, CO, 1998.

AGA. "Field Handling: Hot Dip Galvanizing versus Fusion Bonded Epoxy." American Galvanizers Association, http://www.galvanizert.org/publications/reinforce/RHN97/htm (1999).

Ashley, S. "Rust-Free Rebar." *Mechanical Engineering Magazine*, American Society of Mechanical Engineers May 1995, p. 16.

Blauch, R. (PennDOT) letter to J. Bower (ATLSS), "Application of Stainless and Stainless-Clad Reinforcing bars in Highway Construction." W.O. 4, Materials Partnership, March 30, 2000.

Clarke, J. L. "Current Practice Sheet No.114 - Fibre-Reinforced Plastic Reinforcement for Concrete." *Concrete* January 1999, pp 15-17.

Clear, K. C. "Effectiveness of Epoxy-Coated Reinforcing Steel – Final Report." Canadian Strategic Highway Research Program Project No. 1283, Ottawa OT, 1992, 128 pp.

Composites Institute. "Fiber-Reinforced Polymer (FRP) Composite Dowel Bars— a 15-year Durability Study." Market Development Alliance FRP Dowel Bar Team, Harrison, NY (1999).

Cryotech. http://www.cryotech.com/cma.htm. 5/25/00 (1998).

FHWA. "Materials and Methods for Corrosion Control of Reinforced and Prestressed Concrete Structures in New Construction," Office of Infrastructure R&D, Report No. FHWA-RD-00-081 (2000).

Galvarebar. "The Tempcore Process." http://www.galvarebar.com/tempi.html 6/14/99 (1999).

Kiss, D. J. and T.A. Hill. "Polymer Fibers." *Structural Engineer, Civil Engineering News, Inc.*, Alpharetta, GA, March 2000, pp 38-40.

McGurn, J. F. *Stainless Steel Reinforcing Bars in Concrete.* ICCRRCS, Orlando, FL, December 7-11. 1998.

Mietz, J. "Electrochemical Rehabilitation Methods for Reinforced Concrete Structures, A State of the Art Report." Institute of Materials Communications LTD., London, 1998.

MMFX. "Corrosion Resistant Steel", MMFX Steel Corporation of America, Newport Beach, CA 92660, December, 1999.

NCHRP. "NCHRP Summary of Progress – December 31, 1999." Transportation Research Board, National Research Council, National Academy Press, Washington, DC.

Ormsby, W.C. "New Technologies Improve Cost-Effectiveness of CMA" http://www.tfhrc.gov/pubrds/novdec99/cmaupdate.htm. 5/13/00 (1999).

Pamukcu, S., H. Moo-Young, and D. Burleigh. *Feasibility of the Use of Cathodic Protection and Electro-Chloride Extraction Technology for Structures in Pennsylvania*, Work Order No. 5, Research Program 359631, Transportation Materials Partnership, Pennsylvania Department of Transportation, Harrisburg, PA (1999).

Popular Science. "Rust-Resistant Steel." Popular Science Magazine 8th Annual What's New Awards, December 1995.

Thomas, G. "New DFM Low Carbon Formable, Corrosion Resistant Steels." Department of Materials Science and Mineral Engineering, University of California-Berkeley, April 1998.

Tikalsky, P. J. and A. Scanlon. *High Performance Concrete*, PennDOT Research, Agreement No. 359629, Work Order 3 (2000).

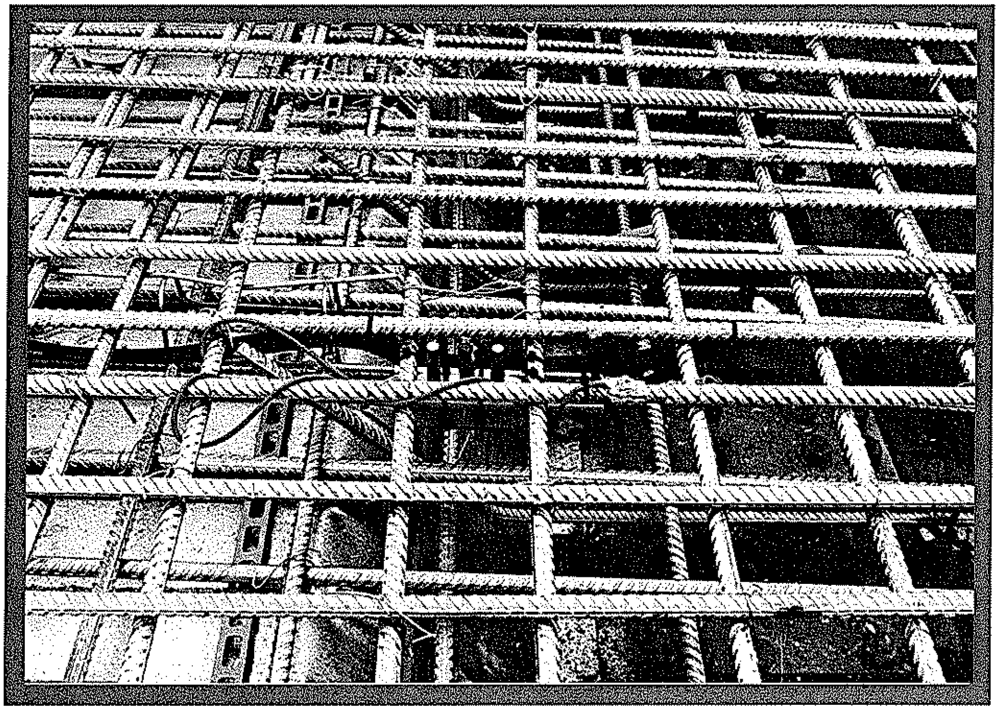
Trejo, D., P. J. M. Montiero, B. C. Gerwick, and G. Thomas. "Microstructural Design of Concrete Reinforcing Bars for Improved Corrosion Performance." *ACI Materials Journal* American Concrete Institute 97: 1 (2000), pp 78-83.

U.S. DOT. *Transportation Researchers Find Unusual Source For Environmentally Friendly Snow and Ice Control.* U.S. Department of Transportation, http://www.dot.gov/affairs/1999/fhwa7699.htm. 5/13/00 (1999).

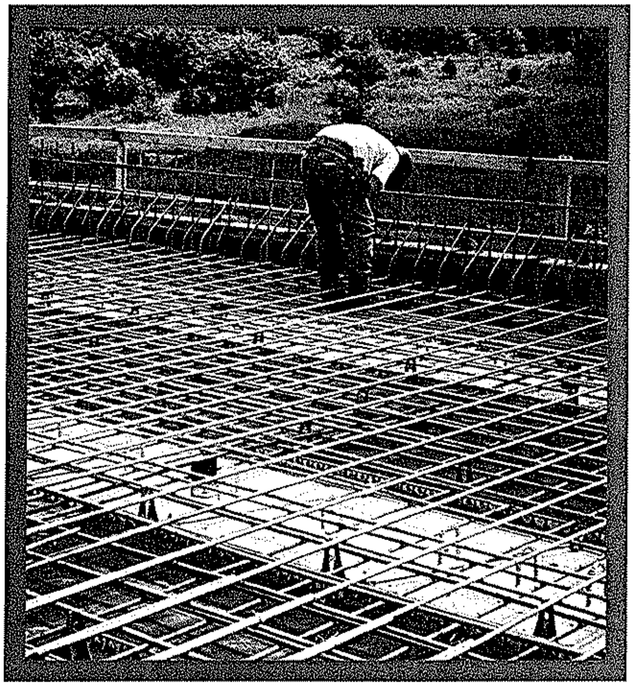
Virmani, Y. Paul and G. G. Clemena. "Corrosion Protection- Concrete Bridges" Publication No. FHWA-RD-98-088 (1998). http://www.tfhrc.gov/structur/corros/foreword.htm.

Zheng, H., and A. A. Abel. "Fatigue Properties of Reinforcing Steel Produced by TEMPCORE Steel." *Journal of Materials in Civil Engineering*, American Society of Civil Engineers 11:2 (May 1999) pp. 158-165.

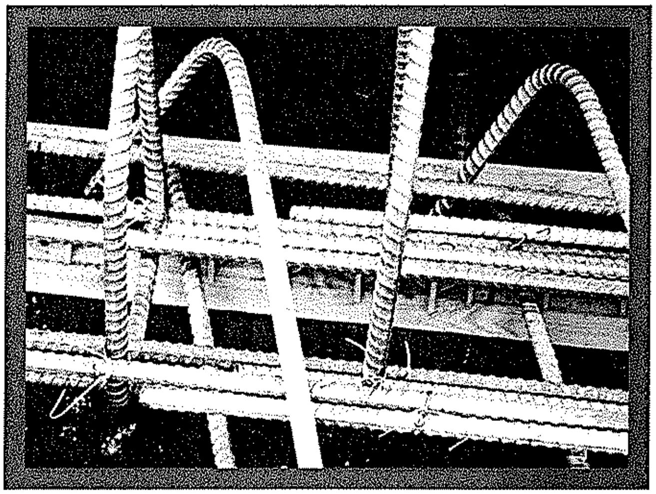
Zia, P., S. Ahmad, and M. Leming. "High-Performance Concretes. A State of the Art Report, 1989-1994." Publication Number FHWA-RD-97-030 (1997). http://www.tfhrc.gov/structur/hpc/hpc2/contnt.htm. 5/25/00.



Garden State Parkway at State Rt. 80
Duplex alloy 2205 rebars



Mullet Creek Bridge,
Rt. 407, Ontario
Austenitic 316 LN rebars



(Photos courtesy of SSINA)

Figure 1. Stainless Steel Reinforcing Bar Installations

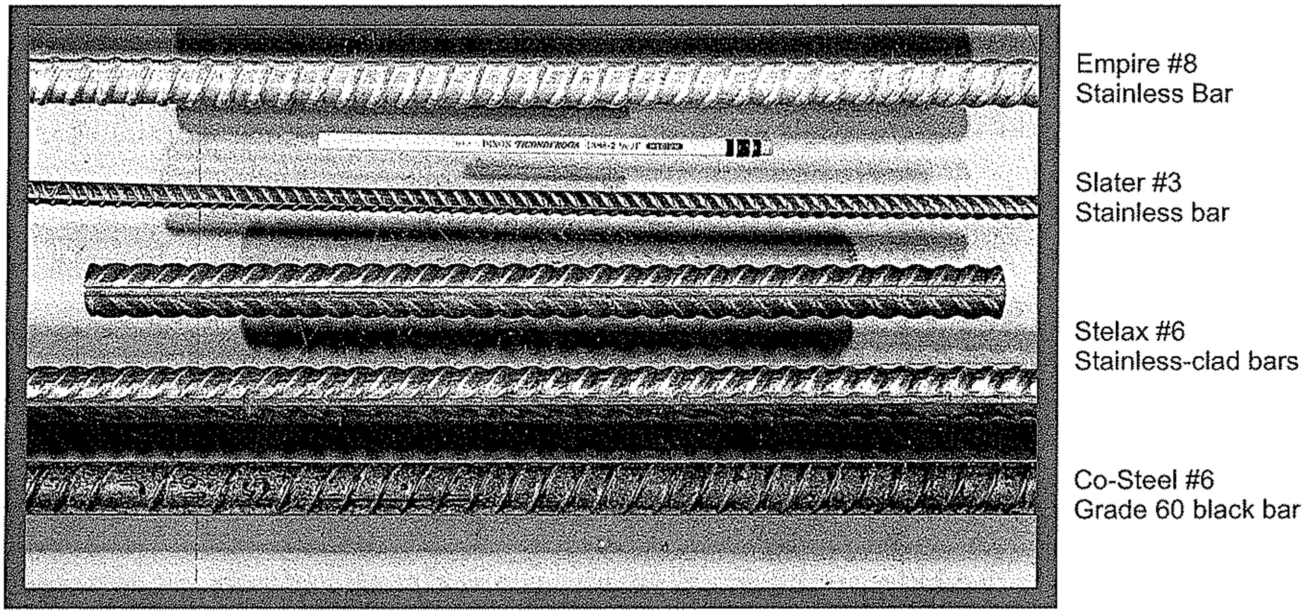
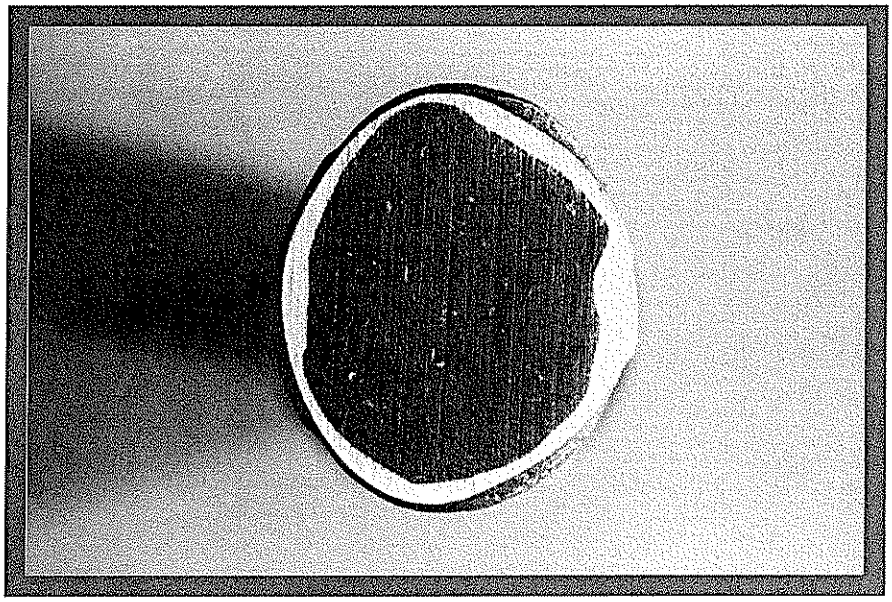
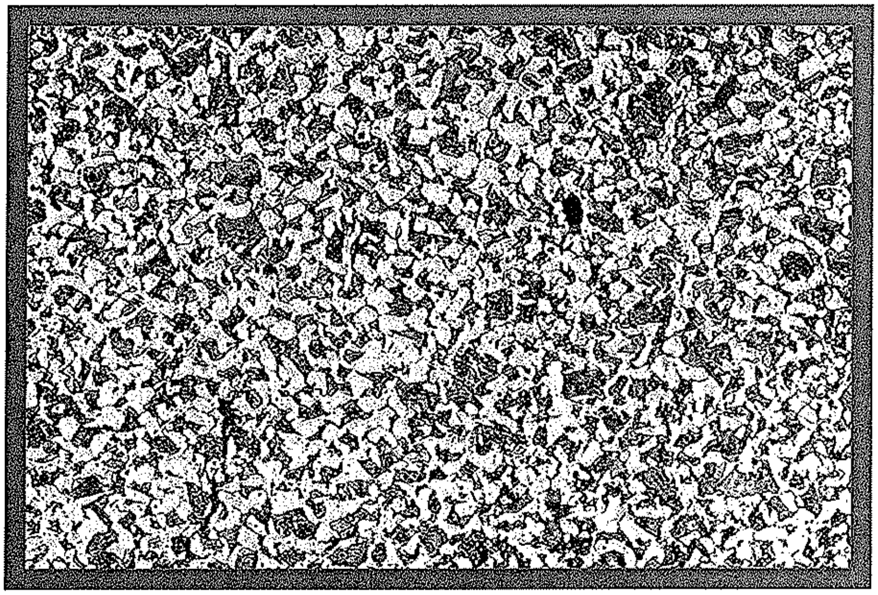


Figure 2. Stainless, Stainless-Clad, and Black Reinforcing Bars (7/2000/14-5)



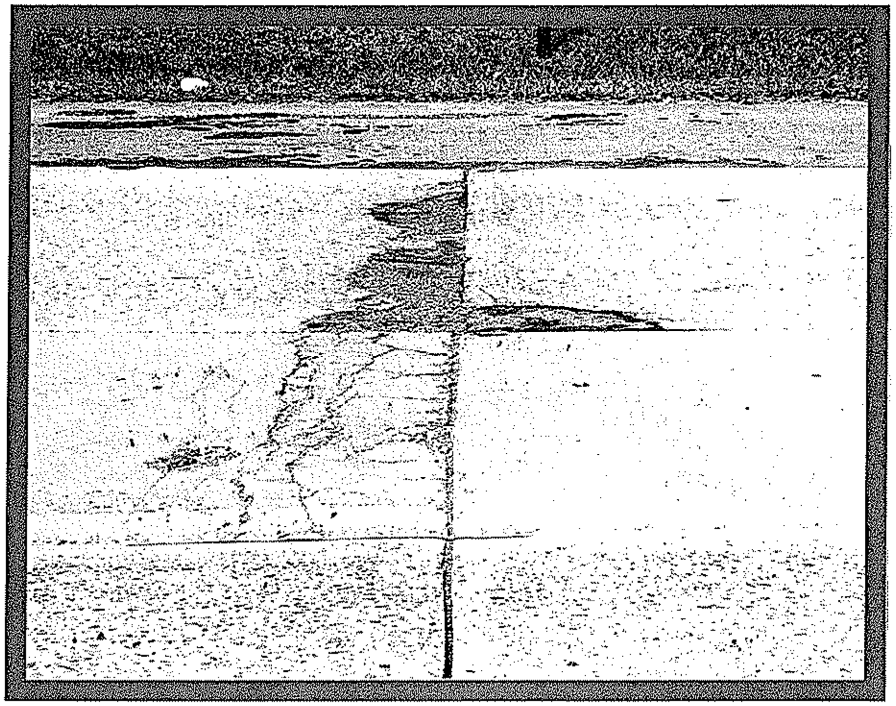
(a) Cross-section showing variation in thickness of stainless cladding (light outside ring) (3/2000/18-1)



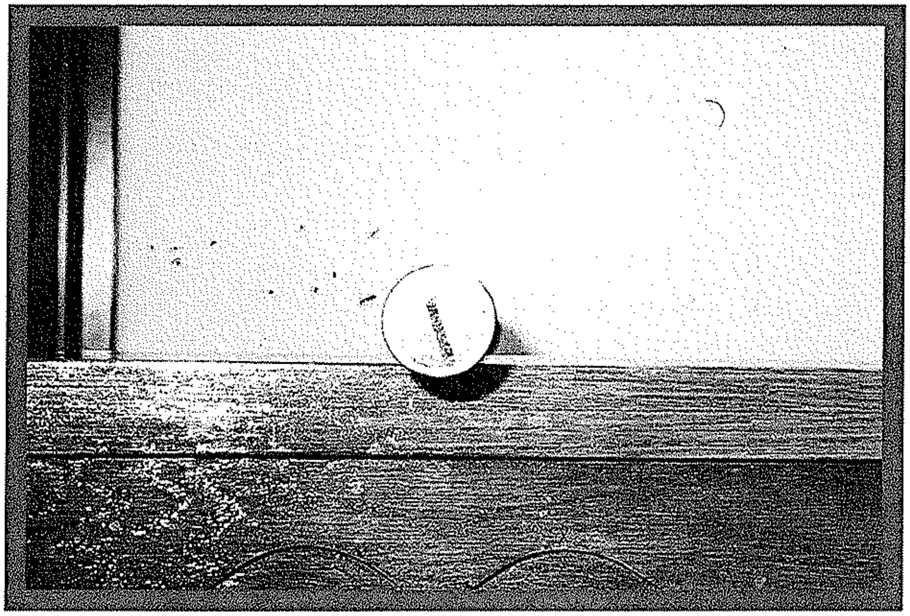
(b) Uniform pearlite-ferrite microstructure

(Photos courtesy of SSINA)

Figure 3. Cross-section through Stelax stainless-clad reinforcing bar and microstructure of carbon-steel core



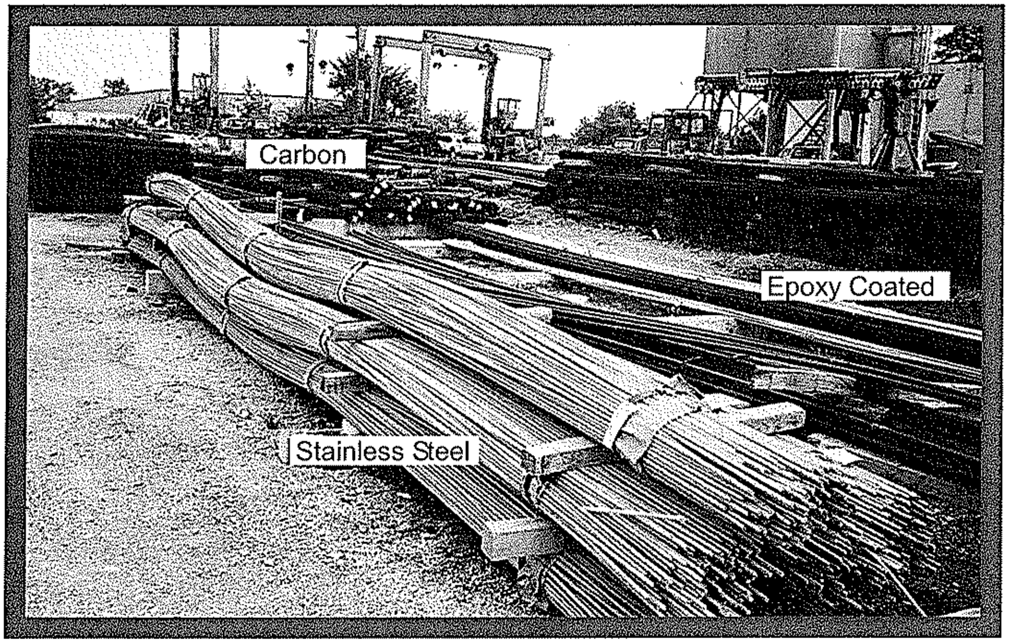
(a) Distress at highway joint on Rt. 155, Albany, NY caused by corrosion of carbon steel dowel bar



(Photos courtesy of SSINA)

(b) Cross-section of grout-filled stainless steel tubular Dowel bar for use on Wisconsin Rt. 29

Figure 4. Stainless steel dowel bars



(Photos courtesy of SSINA)

Figure 5. Stainless steel rebar in precast-concrete yard near carbon steel and epoxy-coated rebars

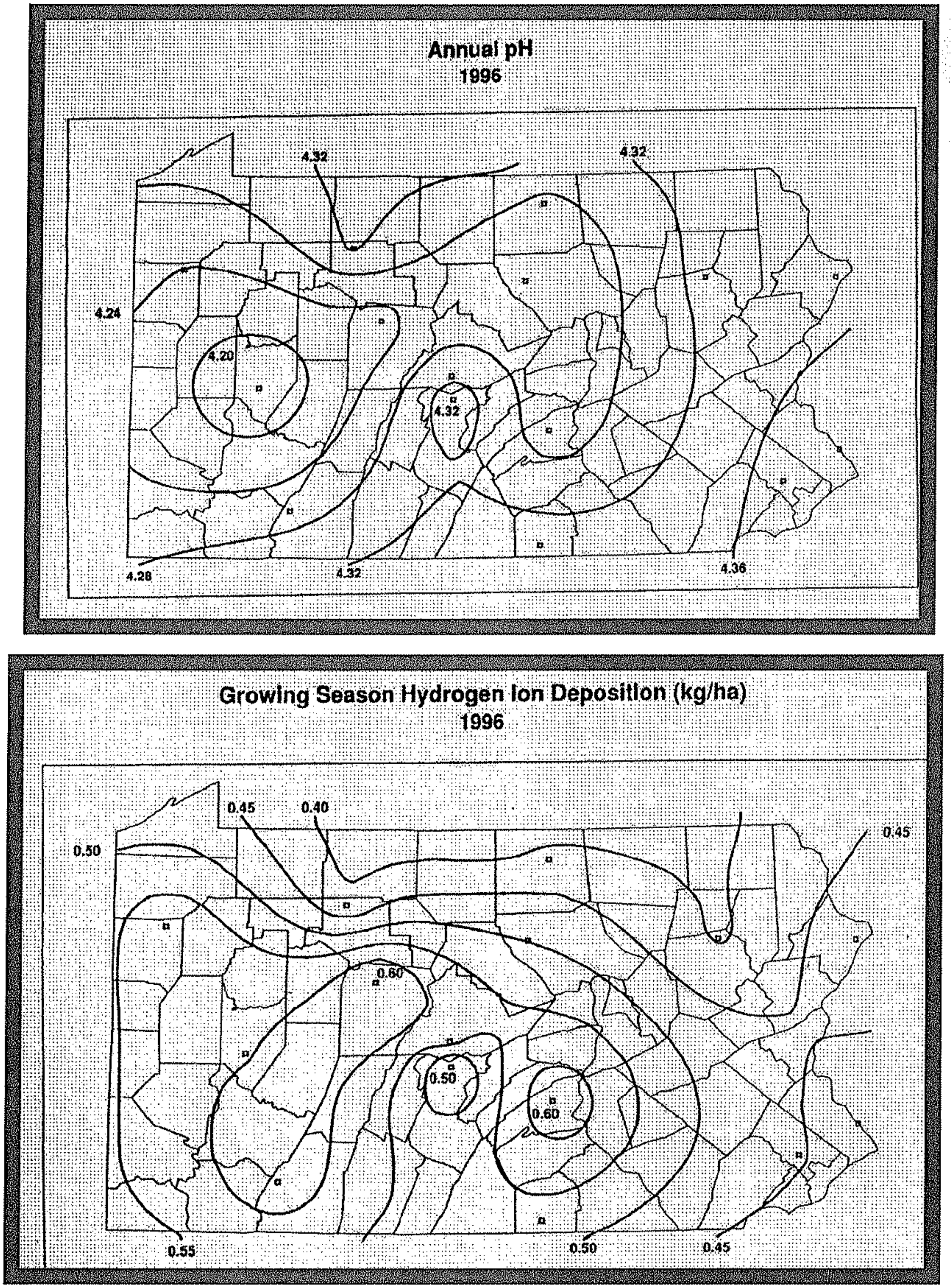
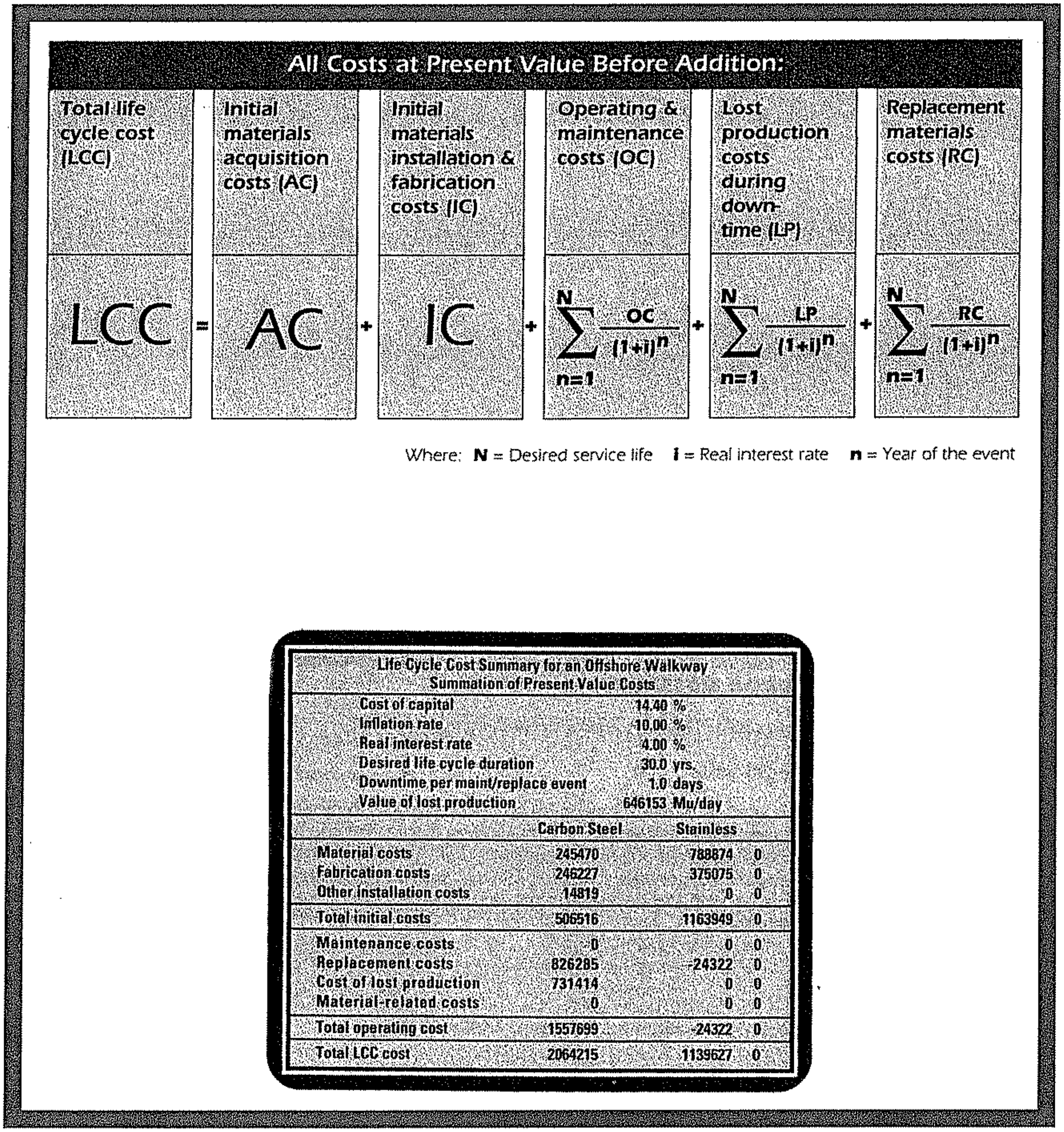


Figure 6. Factors Related to Acid Rain Effect on Pavement Reinforcing



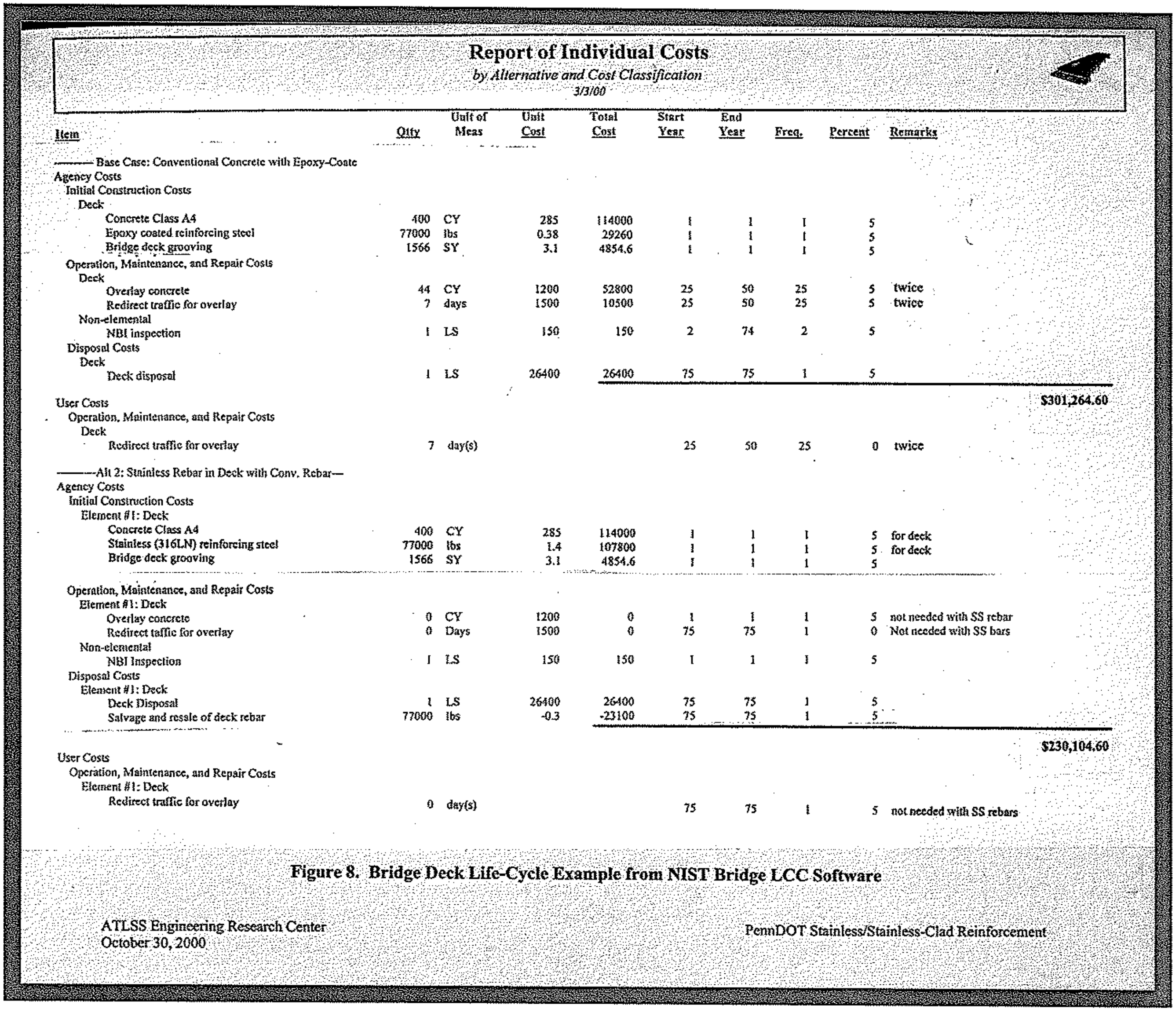
$$LCC = AC + IC + \sum_{n=1}^{N} \frac{OC}{(1+i)^n} + \sum_{n=1}^{N} \frac{LP}{(1+i)^n} + \sum_{n=1}^{N} \frac{RC}{(1+i)^n}$$

Where: **N** = Desired service life **i** = Real interest rate **n** = Year of the event

Life Cycle Cost Summary for an Offshore Walkway
Summation of Present Value Costs

Cost of capital	14.40 %		
Inflation rate	10.00 %		
Real interest rate	4.00 %		
Desired life cycle duration	30.0 yrs.		
Downtime per maint/replace event	1.0 days		
Value of lost production	646153 Mu/day		
	Carbon Steel	Stainless	
Material costs	245470	788874	0
Fabrication costs	246227	375075	0
Other installation costs	14819	0	0
Total initial costs	506516	1163949	0
Maintenance costs	0	0	0
Replacement costs	826285	-24322	0
Cost of lost production	731414	0	0
Material-related costs	0	0	0
Total operating cost	1557699	-24322	0
Total LCC cost	2064215	1139627	0

Figure7. Life-Cycle Cost Equation and Example



Report of Individual Costs

by Alternative and Cost Classification

3/3/00

Item	Qty	Unit of Meas	Unit Cost	Total Cost	Start Year	End Year	Freq.	Percent	Remarks
——— Base Case: Conventional Concrete with Epoxy-Coate									
Agency Costs									
Initial Construction Costs									
Deck									
Concrete Class A4	400	CY	285	114000	1	1	1	5	
Epoxy coated reinforcing steel	77000	lbs	0.38	29260	1	1	1	5	
Bridge deck grooving	1566	SY	3.1	4854.6	1	1	1	5	
Operation, Maintenance, and Repair Costs									
Deck									
Overlay concrete	44	CY	1200	52800	25	50	25	5	twice
Redirect traffic for overlay	7	days	1500	10500	25	50	25	5	twice
Non-elemental									
NBI inspection	1	LS	150	150	2	74	2	5	
Disposal Costs									
Deck									
Deck disposal	1	LS	26400	26400	75	75	1	5	
User Costs									$301,264.60
Operation, Maintenance, and Repair Costs									
Deck									
Redirect traffic for overlay	7	day(s)			25	50	25	0	twice
———Alt 2: Stainless Rebar in Deck with Conv. Rebar—									
Agency Costs									
Initial Construction Costs									
Element #1: Deck									
Concrete Class A4	400	CY	285	114000	1	1	1	5	for deck
Stainless (316LN) reinforcing steel	77000	lbs	1.4	107800	1	1	1	5	for deck
Bridge deck grooving	1566	SY	3.1	4854.6	1	1	1	5	
Operation, Maintenance, and Repair Costs									
Element #1: Deck									
Overlay concrete	0	CY	1200	0	1	1	1	5	not needed with SS rebar
Redirect taffic for overlay	0	Days	1500	0	75	75	1	0	Not needed with SS bars
Non-elemental									
NBI Inspection	1	LS	150	150	1	1	1	5	
Disposal Costs									
Element #1: Deck									
Deck Disposal	1	LS	26400	26400	75	75	1	5	
Salvage and resale of deck rebar	77000	lbs	-0.3	-23100	75	75	1	5	
									$230,104.60
User Costs									
Operation, Maintenance, and Repair Costs									
Element #1: Deck									
Redirect traffic for overlay	0	day(s)			75	75	1	5	not needed with SS rebars

Figure 8. Bridge Deck Life-Cycle Example from NIST Bridge LCC Software

ATLSS Engineering Research Center
October 30, 2000

PennDOT Stainless/Stainless-Clad Reinforcement

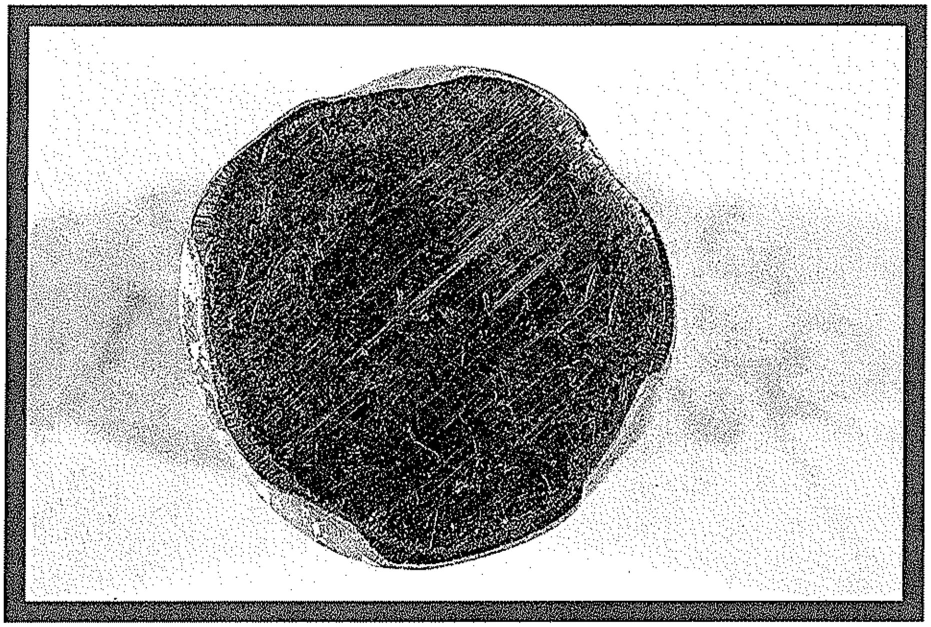
Grade 60 epoxy-coated bar

FRP composite bar from
Marshall Industries

Grade 75 galvanized bars

Bent-after-coating
Epoxy-coated bar

(a) Competitive bars (8/2000/19-10)



(b) Cross-section through epoxy coated bar (8/2000/1-10)

Figure 9. Competitive Reinforcing Bar Styles