RECLAMATION

*Managing Water in the West*

# Alternative Reinforcement for Concrete in Corrosive Environments

**Research and Development Office**
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**Final Report ST-2016-0620-01**


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High performance concrete (HPC), in combination with routine inspection and maintenance often succeeds in preventing or limiting rebar corrosion and related damage. Under certain environmental conditions however, corrosion can initiate, remain undetected and/or unrepaired, and cause damage to a structure. Several reinforcement alternatives such as stainless steel and zinc-coated steel have been in use for several decades. More recently, fiber reinforced polymer (FRP) composites (e.g., glass, carbon, and basalt) have been engineered and used in full-scale construction projects. This study shows that a determination of the viability of alternatives to plain steel rebar should not be based on reinforcement corrosion performance alone but should also include consideration of a structure's design, construction, operating environment, and expected lifetime plus the lifecycle costs associated with maintenance, repair, and replacement. In addition, the use of FRP rebar as concrete reinforcement should be further investigated.

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# Executive Summary

High performance concrete (HPC), in combination with routine inspection and maintenance usually prevents or limits rebar corrosion-related damage. Under certain environmental conditions however, corrosion can occur, and remain undetected until damage occurs.

This study was conducted to answer the following questions:

1. What alternative concrete reinforcement materials exist for use in corrosive environments? and

2. How do these alternatives compare to steel reinforcement with respect to cost, performance, and durability?

In addition to answering these questions, the study noted that several reinforcement alternatives such as stainless steel and zinc-coated steel have been in use for several decades. More recently, fiber reinforced polymer (FRP) composites (e.g., glass, carbon, and basalt) have been engineered and used in a limited number of large construction projects. The use of FRP rebar has enabled concrete cover depth reduction and provided other benefits related to fundamental structural design possibilities and cost reduction. While stainless steel rebar has established itself as a viable corrosion-resistant alternative to plain steel, FRP rebar could offer desirable performance characteristics in certain types of civil infrastructure construction projects.

When deciding whether to use a concrete reinforcement material other than plain steel rebar, corrosion performance and initial cost are unquestionably very important. Consideration should also be given however to things such as the particular structure's design/geometry, specialized construction requirements, operating environment, and expected/required lifetime. In addition, life cycle cost analysis (LCCA) must be performed to evaluate the relevance of additional specific costs associated with raw materials, expected maintenance and repairs, replacement costs, and adverse impact to users.

We recommend that the feasibility of using FRP (especially basalt) rebar in Reclamation structures be evaluated as an alternative to plain steel rebar in corrosive environment applications.

# Introduction

Structural concrete is often reinforced with plain carbon steel.  Under certain conditions, the steel is subject to corrosion and this can damage both the steel and the concrete.  Historically, designers have specified the use of high performance concrete (HPC) to increase a structure's ability to resist reinforcing steel corrosion.  This, in combination with routine inspection and maintenance often succeeds in preventing corrosion or at least limiting corrosion-related damage. Under certain environmental conditions however, corrosion can initiate.  If corrosion remains undetected and/or unrepaired, it could reduce the structure's service-life, capacity, and safety.

A recent Virginia Department of Transportation (VDOT) report concluded that "major efforts have been devoted to improving the quality of concrete (HPC can provide a bridge service life of more than 75 years) but little attention has been devoted to using longer lasting reinforcement" (Sharp and Sprinkel, 2012).  While this might be true in terms of actual field implementation, several reinforcement alternatives such as stainless steel and zinc-coated steel have been in use for several decades in a limited number of applications.

Recently, several fiber reinforced polymer (FRP) composites have been engineered and used in some large construction projects.  Given that many of Reclamation's reinforced concrete structures are exposed to corrosive environments, corrosion-resistant types of reinforcement could be desirable for use in future projects.  This report provides basic descriptions of several of these alternative materials and in-depth descriptions of three fiber reinforced polymer (FRP) composite materials, namely glass, carbon, and basalt.

Ultimately, this study answers the key questions: what alternative concrete reinforcement materials exist for use in corrosive environments, and how do these alternatives compare to steel reinforcement with respect to cost, performance, and durability?

# Conclusions

- Stainless steel and stainless steel clad rebar (SCR) are highly resistant to corrosion and can possibly provide more than 100 years of maintenance-free service life.

- The use of fiber reinforced polymer (FRP) rebar as an alternative to plain steel rebar in corrosive environment applications should be evaluated.  In particular, basalt fiber reinforced polymer (BFRP) rebar should be further investigated given its apparent desirable characteristics with respect to long-term performance and cost.

- FRP rebar's reduced concrete cover requirements and other benefits related to fundamental structural design possibilities might provide additional cost savings in Reclamation reinforced concrete projects.

# Recommendations

- Recognize all of the non-economic considerations beyond corrosion performance when deciding whether or not to use an alternative concrete reinforcement material. In particular, consider the particular structure's design/geometry, specialized construction requirements, operating environment, expected/required lifetime, etc.

- Recognize all the economic/cost considerations beyond initial material cost at project outset; perform life-cycle cost analysis (LCCA) when selecting a suitable alternative to mild steel reinforcement for corrosive service environments. In particular, consider the necessity of using any specialized trades for installation/construction, long-term maintenance/repair, replacement, economic consequences of service interruptions to users, etc.

- Evaluate the feasibility of using FRP rebar (especially basalt) as an alternative to plain steel rebar in future Reclamation reinforced concrete construction projects, particularly those that involve corrosive environments. Feasibility evaluation should answer the following specific questions:

    1. To what degree has Reclamation's existing reinforced concrete infrastructure inventory been adversely affected by corrosion?

    2. Can FRP rebar (esp. basalt) match the corrosion performance of stainless steel rebar?

    3. To what extent, if any, could concrete chemistry (i.e., ordinary Portland cement (OPC) or high performance concrete (HPC)) negatively affect basalt rebar durability and performance?

    4. In what particular types of Reclamation infrastructure projects can the use of FRP rebar be implemented?

# Background

## Plain Steel Reinforcement

Concrete has a high compression strength but low tensile strength. In contrast, steel has a very high compression strength (approximately ten times as great as that of concrete) and an even higher tensile strength (approximately one hundred times greater than that of concrete). Steel does however have a much higher cost than concrete (as much as twenty five times greater). Accordingly, reinforced concrete design emphasizes efficient use of steel. Efficient use of steel can amount to as little as one or two percent of the total reinforced concrete volume, as in the case of a slab or beam, or as much as five to ten percent of the total volume in the case of a column.

Steel has been and continues to be a very popular material for use in concrete reinforcement. Its popularity is derived not only from its strength and ductility but from other factors such as its coefficient of thermal expansion and bond strength to concrete. Steel's coefficient of thermal expansion is similar to that of concrete. When a steel-reinforced concrete member expands or contracts due to changes in the ambient temperature, the two materials expand or contract by approximately equal amounts. Differences in thermal expansion coefficients of the concrete and the reinforcement could give rise to stresses that would reduce the concrete's ability to transfer tensile stresses to the rebar and possibly cause a structural member to disintegrate.

The bond between the embedded steel and the concrete is strong and the strength of this bond is enhanced by deformations that are formed on the surface of the steel during rebar manufacture. The concrete-steel bond allows for the transfer of compressive and tensile stresses thus achieving reinforced concrete's design intent.

As mentioned in the Introduction, embedded steel is subject to corrosion under some conditions; very often however, reinforcing steel in concrete does not corrode. The observed corrosion resistance can be attributed to a protective passive film that is formed on the surface of the steel when the steel is exposed to the high alkalinity of the concrete. This passive film can protect the steel from corrosion indefinitely in ideal environments but the film's protective ability can be compromised by certain environment-related phenomena such as concrete carbonation and/or chloride ion contamination. In the case of carbonation, a reduction in concrete pore water pH results from concrete pore water interaction with atmospheric carbon dioxide. The resulting low pH causes the passive film to breakdown. In the case of chloride contamination, chloride ions can either occur naturally in the service environment (e.g., seawater) or be applied to the exterior surface of the structure (e.g., deicing salts). In some cases, chlorides can come from concrete making materials, including some concrete admixtures. For external chloride sources, the chloride ions diffuse through the concrete from the exterior concrete surface to the surface of the embedded reinforcing steel. When the ion concentration exceeds a value known as the chloride threshold, the passive film is vulnerable to breakdown. In both cases, the loss of the passive film could allow corrosion to proceed as in the case of unprotected steel. In cases that involve both carbonation and chloride contamination, corrosion can initiate and progress rapidly.

Other factors such as service environment temperature, humidity, and sunlight exposure can also affect the ability of reinforcement, regardless of its material, to perform as intended.

High ambient relative humidity can effectively decrease concrete's resistivity and increase the chloride diffusion rate. These things can enable higher corrosion rates, but can also increase the "throwing power" of natural cathodic protection provided by nearby corroding regions of the rebar cage. Moderate ambient relative humidity (i.e., between approximately 50 to 70%) can increase the tendency for concrete to carbonate and this can effectively decrease pore water pH. Carbonation risk is generally considered to be negligible when relative humidity is lower than approximately 25% or higher than approximately 75%.

In addition to thermal expansion, bond strength, and corrosion vulnerability of a candidate reinforcement material, consideration must be given to creep, fatigue, and concrete cover depth (the distance between the outer concrete surface of the structural member and the embedded reinforcement). Concrete cover protects the reinforcing steel from excessive moisture and also can effectively control or extend the amount of time required for chlorides and/or the carbonation front to travel through the concrete to the steel. Creep and fatigue of both the reinforcement and the concrete can cause substantial changes in a structure's capacity, safety, and durability.

In spite of reinforcing steel's desirable properties, the possibility of corrosion-induced structural deficiencies and the subsequent cost of maintenance, repairs, and/or replacement must be considered in the material selection process. Many Reclamation structures such as bridges, buildings, tunnels, and dams feature reinforced concrete and some of these structures are exposed to chlorides and/or are subject to carbonation. As expectations for greater structure service life increase and allowable maintenance and repair costs decrease, interest in corrosion-resistant concrete reinforcement grows.

## Other Types of Reinforcement

Corrosion-resistant rebar materials (e.g., solid stainless steel, low-nickel austenitic stainless steels, and both ferritic and martensitic chromium steels) have been used in a substantial number of large-scale civil infrastructure projects (Moreno et al., 2008). In addition, plain steel rebar that has been galvanized, epoxy-coated, or clad in stainless steel has also been used. Carbon-, glass-, and basalt-fiber reinforced composite rebar has also emerged in recent decades and gained increasing support in the construction industry. Table 1 presents a comparison of the approximate time of market introduction for each alternative rebar type.

A University of Waterloo (Ontario, Canada) report (Hansson et al. 2000) that addressed "Corrosion Strategies for Ministry Bridges", stated that the field performance of a particular type of rebar depends largely on the specific environment, design factors, and construction practice. Of equal or greater importance, the perception of favorable performance of reinforcement studied in various investigations is very much dependent on what was/was not investigated and/or measured by Hansson et al. (2000).

In order for any particular concrete reinforcement candidate to merit consideration for any particular application, embedded concrete reinforcement materials must be chemically and dimensionally stable in chloride- and sulfate-contaminated environments, moist/submerged environments, and in the high pH concrete pore water solution.

Note that some alternative types of rebar have already been found unacceptable and thus denied consideration in future projects. For example, the Virginia Department of Transportation (VDOT) discontinued the use of epoxy coated and galvanized bars in September 2010 (Sharp and Sprinkel, 2012).

Table 1.—Approximate market introduction date of various rebar types

| Rebar material/type | Market introduction date (approximate) |
|---|---|
| Basalt fiber | 1995 |
| Carbon fiber | 1990 |
| Epoxy-coated | 1973 |
| Galvanized | 1905 |
| Glass fiber | 1960 |
| Low-carbon chromium steel | 2001 |
| Plain steel | 1850 |
| Stainless steel clad plain steel | 1970 |
| Stainless steel rebar | 1938 |

A brief description of each rebar type follows.

## Solid Stainless Steel

Stainless steel rebar consists of iron alloyed with chromium (at least 10.5% by weight) and various amounts of other elements such as nickel and molybdenum. This alloying effectively gives stainless steel a greater ability to resist corrosion than plain steel. Several different types, categories, and grades of stainless steel are available; distinctions are based on differences in chemical composition, manufacturing processes, and extent of cold working (Kahl, 2012).

Stainless steels can be divided into five broad categories according to alloy chemistry and microstructure: austenitic, ferritic, duplex (austenitic-ferritic), martensitic, and precipitation hardening (Kahl, 2012). Hartt et al. found that the most common types of stainless steel rebar that various state departments of transportation (DOTs) have used are 316LN austenitic and 2205 duplex (Hartt et al., 2006); other common types include XM-28 and 2304. ASTM Standard A955/A955M specifies the required mechanical properties and corrosion resistance for stainless steel used as concrete reinforcement.

Stainless steel's chloride threshold can be more than 20 times greater than that of plain steel. This enables stainless steel rebar to remain unaffected by chlorides for several decades in environments with chloride contamination levels that would readily destroy plain steel's protective passive film (MacDonald, 1998). Stainless steel reinforcement was used as early as the late 1930s (Kahl, 2012) and has attained a substantial level of use since then. The Virginia Center for Transportation Innovation and Research has reported that 20% of the 8.8 million pounds of corrosion resistant rebar used by VDOT between 2010 and 2012 was stainless steel (Sharp and Sprinkel, 2012).

Solid stainless steel rebar is largely unaffected by normal transportation, handling, and construction operations. The bars can however be bent, cut, and welded in the field without repair or coating.

## Stainless Steel Clad Plain Steel

Stainless-steel-clad rebar (SCR) consists of plain steel rebar with a thin (less than 1 mm in thickness) outer layer of stainless steel, metallurgically bonded during hot rolling of the bar. Rebar of this type was first developed in the 1970's and has subsequently been used in civil infrastructure applications. Stainless-steel-clad rebar is described as having the high corrosion resistance of stainless steel with the yield strength and elastic modulus characteristics of low-alloy carbon steel; it is said to be tough and not easily scratched or chipped. The consequences of any cladding imperfections and discontinuities depend on the degree of the nonconformity and the resistivity of the concrete (Cui and Sagüés, 2003).

Stainless-steel-clad rebar can be bent, cut, and welded; cut ends may need to be capped or coated. SCR manufacturers assert that their rebar has no special transportation, handling, and construction requirements though they do say that carbon steel bands, tie-wires, and lifts should not be used with SCR. As noted in a survey conducted by the Maine DOT, several state DOTs (Virginia, New York, Michigan, Oregon, and Florida) have allowed the use of SCR. (AASHTO/Maine DOT, 2009). In addition, Kahl observed that a reinforcement design that uses both solid stainless reinforcement and SCR in a single bridge deck can be expected to provide the same maintenance-free service life as a deck that uses only solid stainless reinforcement (Kahl, 2012).

## Microcomposite Steel / ASTM A-1035

Microcomposite rebar consists of uncoated low-carbon chromium steel as typified by the MMFX Technologies Corporation's line of corrosion resistant rebar (ChrōmX®) and addressed in ASTM A-1035. According to MMFX, their patented process "eliminates carbides and the 'battery effect' by forming packets of microcomposite austenite and lath martensite structure, which do not form microgalvanic cells. The microstructural corrosion mechanism existing in conventional steel is eliminated from microstructurally designed MMFX Steels" (MMFX Steel, 2014).

As with solid stainless steel rebar and stainless-steel-clad plain steel rebar, low-carbon chromium steel rebar is intended to obviate the need for application of a corrosion-resistant coating. MMFX Technologies emphasizes the importance of using high performance concrete (HPC) when using ChrōmX®. It should be noted however that HPC is known to be capable of enhancing corrosion performance of reinforced concrete regardless of rebar type.

## Galvanized

Galvanized rebar is simply plain steel rebar coated with zinc (i.e., hot-dip galvanized). The zinc coating serves as both sacrificial protection and as a barrier to chlorides, water, and oxygen for the plain steel. Galvanized steel was first used as concrete reinforcement in the early 1900s and was common by the 1930s.

While the zinc coating on galvanized rebar is not as fragile as an epoxy coating, it should be noted that cut ends, welds, damaged coating surfaces, and any other hardware (e.g. ties) must be coated with a zinc-rich primer prior to concrete placement. UV exposure during transportation, handling, and construction does not affect the integrity of the zinc coating and concrete-rebar bond strength is regarded as excellent. The concrete mix water-to-cement ratio and the concrete pore water pH are significant indicators of projected galvanized rebar corrosion performance and durability; high water-to-cement ratio (i.e., greater than 40-50%, [Clear, 1981] and lower pH (i.e., less than 13.3 [Macias and Andrade, 1987] are favorable).

As indicated above, the Virginia Department of Transportation does not allow the use of galvanized rebar reinforcement (Sharp and Sprinkel, 2012).

## Epoxy-Coated

Epoxy Coated Rebar (ECR) consists of plain steel rebar with an epoxy coating. The coating is intended to serve both as a physical barrier (i.e., to chloride ions, water, and oxygen) and as an electrical insulator that minimizes the flow of corrosion current. Production quality and epoxy coating integrity are significant indicators of the epoxy coating's effectiveness; coating defects and damage leave the plain steel as vulnerable to corrosion as bare, uncoated steel. Epoxy coatings have proven to be susceptible to damage during transportation, handling, and construction. The act of bending epoxy coated rebar (as is commonly done during rebar cage construction) can also damage the coating. Research results have indicated that epoxy coated rebar is as vulnerable to corrosion as uncoated rebar even in cases where the defective or damaged surface area is limited to values as low as 0.5% of the total surface area of the rebar (MacDonald, 1998).

Coating imperfection problems are exacerbated by construction/installation problems (e.g., low concrete cover depth) and detrimental service environment phenomena (e.g., chloride ion contamination, concrete carbonation). Deck cores analyzed by Weyers et al. in a Virginia DOT research study on bridge decks between two and twenty years old revealed that in Virginia the epoxy had debonded from the steel in as little as four years. (Weyers et. al., 2000; Kahl, 2012). The Virginia Center for Transportation Innovation and Research observed that as ECR ages, epoxy loses adhesion to steel, the epoxy permeability increases, and the epoxy itself is susceptible to cracking (Sprinkel et al., 2008). As mentioned above, the use of epoxy-coated rebar, like galvanized rebar, has been deemed unacceptable by some agencies (Sharp and Sprinkel, 2012).

## Glass Fiber Rebar

Glass-fiber-reinforced polymer (GFRP) rebar consists of resin-impregnated glass fibers aligned with the longitudinal axis of the bar. Glass fibers are immune to both chloride contamination and many forms of chemical-induced degradation. The tensile strength of GFRP rebar can be more than 200% that of plain steel but its tensile modulus is only approximately 20% that of plain steel. GFRP bar is electrically and thermally nonconductive and it typically weighs approximately 25% of an equally sized plain steel bar.

GFRP rebar's low tensile modulus can make it unsuitable for structural concrete applications that involve significant span lengths. GFRP non-conductivity makes it well suited to applications that involve close proximity to equipment sensitive to electrical/magnetic interference (e.g., compasses, electronic calibration devices, and magnetic resonance imaging machines).

GFRP rebar must be protected from significant bending during transportation, handling, and construction as bending can damage or break the glass fibers. GFRP is known to absorb water through its core and this can effectively change the rebar's mechanical properties.

## Carbon Fiber

Carbon fiber-reinforced polymer (CFRP) rebar consists of carbon fibers in an epoxy resin matrix and, like GFRP, the fibers are aligned with the longitudinal axis of the bar (Figure 1). Carbon fibers, like glass fibers, are immune to both chloride contamination and many forms of chemical-induced degradation. As is the case with GFRP, the tensile strength of CFRP rebar can be more than 200% that of plain steel and it has significantly less weight than steel, approximately 20% of an equally sized plain steel bar. CFRP rebar is practically electrically and thermally nonconductive and is, like GFRP, well suited to applications that involve close proximity to equipment sensitive to electrical/magnetic interference (e.g., compasses, electronic calibration devices, and magnetic resonance imaging machines).

CFRP is usually installed by the near-surface-mounted technique in which the reinforcement bars are inserted into grooves cut into the substrate concrete and bonded with epoxy resin. CFRP rebar must be protected from significant bending during transportation, handling, and construction as bending can damage or break the fibers. It must be protected from direct sunlight/UV exposure. CFRP and other fiber reinforced polymer composites are however easier to carry and move given their low relative weight.

The initial cost of CFRP is generally higher than that of plain steel rebar and is roughly comparable to the cost of epoxy-coated steel rebar. In most cases however, CFRP's lifecycle cost (LCC) is much less than that of steel.

**Figure 1.—Carbon fiber reinforced polymer rebar: molded surface protrusions that enhance rebar-to-concrete bond. (http://www.zacarbon.com/cfrp-rebar, 2016)**

## Basalt Fiber

Like GFRP and CFRP, basalt fiber reinforced polymer (BFRP) rebar consists of fibers contained in a polymer matrix. Basalt fibers do however offer superior performance to glass and significantly lower cost than carbon fibers. With respect to glass fibers, basalt has higher tensile strength and modulus of elasticity, greater tolerance to thermal changes, and greater stability in both acidic and alkaline environments. Furthermore, basalt does not absorb water through its core in the way that glass fibers do. Basalt fibers are completely nonconductive making BFRP an even better choice in applications sensitive to electrical and magnetic interference.

The tensile strength of basalt fibers can be more than 1,000% that of plain steel and fiber weight can be as low as 10% that of an equal volume of steel. Most notably, basalt rebar can return to its original shape after being bent, once bending stress is released. Basalt rebar can be permanently bent given exposure to heat and is available in pre-made corners, angles, loops, etc. (Figure 2) Transportation, handling, and construction don't involve any special considerations. Basalt rebar's very low weight can enable a coil several thousand feet long to be lifted by one construction worker (depending on the bar diameter) without the need of special equipment or a forklift. BFRP rebar's thermal expansion coefficient is the same as that of plain steel rebar.

“image 9”, http://www.monolithic.org/link-to/basalt-fiber-rebar

“image 10”, http://www.monolithic.org/link-to/basalt-fiber-rebar

**Figure 2.—Basalt rebar prefabricated in various shapes to accommodate specific design geometries (left); Basalt rebar cages prior to concrete placement in a conventional construction application (right).**

The cost of basalt rebar is greater than that of steel but its invulnerability to corrosion can effectively reduce its life-cycle cost and enable very low concrete cover depth permitting manufacture of concrete beams with thickness as low as 1 inch.

# Other Considerations

## Structure Design

The nature of a structure and its intended use may influence rebar type selection. With regard to a typical reinforced concrete structure such as a bridge, VDOT distinguishes between three different functional classifications based on expected load, traffic volume, and site locale (e.g., urban or rural) (Sharp and Sprinkel, 2012). This classification specifies the use of low-carbon chromium steel rebar under “light” conditions, stainless steel clad rebar under “moderate” conditions, and the use of solid stainless steel rebar under the “most severe” conditions. Presumably, alternative rebar candidates such as GFRP, CFRP, and BFRP could, after demonstrating appropriate performance capability, be used in future applications of this type. Of course, any particular type of rebar with high corrosion resistance may or may not be the best material for use in design/applications that do not demand this particular property. In addition, it should be noted that a structure’s design weight/dead load could vary significantly according to the actual reinforcement type selected.

## Rebar Transportation/Construction/Storage

Transportation of rebar can lead to damage of the rebar or the bar coating from exposure to UV rays, humidity changes, precipitation, and temperature fluctuations, etc. A particular material's special transportation requirements could affect transportation costs, shipping routes, carrier types, delivery times, etc.

Rebar can be subjected to rough handling during loading/unloading, storage, assembly, and placement; the characteristics of any particular rebar type might necessitate special care. For example, the epoxy coating on epoxy-coated rebar (ECR) is vulnerable to damage during all phases of the transport and construction processes. Repair of damage can increase construction costs and cause construction schedule delays. As another example, stainless steel is vulnerable to surface freckling or discoloration due to contamination by direct contact with plain steel in the form of binding, shipping, and handling materials and equipment. The presence of these (likely inconsequential) imperfections could nonetheless cause rejection of otherwise suitable stainless steel reinforcement.

## Economics

Raw material costs vary according to rebar type and cost variations can be significant. Solid stainless steel rebar, for example, can cost twice as much as stainless-clad rebar and three to five times as much as ECR. ECR can cost up to one-and-a-half times the cost of plain steel rebar. The price of a particular type of rebar can also be subject to periodic price fluctuations given its constituent materials. The cost of stainless steel will fluctuate with the costs of nickel and molybdenum (which cost up to ten times as much as chromium); the cost of stainless steel alloys with greater nickel contents may be subject to the greatest fluctuation (Hansson et al. 2000). Despite significant cost variations and fluctuations, the additional cost of using one type of steel instead of another (e.g., stainless instead of plain) might amount to a total project cost difference of only five to ten percent.

In addition to material cost considerations, other economic factors such as type-specific skilled labor costs, long-term structure maintenance and repair, and expected structure service lifetime must be considered. Furthermore, selective use of multiple types of rebar in a single structure (e.g., stainless and stainless-clad reinforcement) could yield cost savings. For these reasons, economic comparison of rebar type options often involves life cycle cost analysis (LCCA). LCCA involves consideration of many of the above factors and could even include costs associated with impact (e.g., water outages, decreased crop output, missed agricultural opportunities) to users. LCCA recognizes that the incidental costs associated with a water outage could exceed the extra cost of stainless steel rebar, for example. LCCA is intended to facilitate comparisons of different scenarios rather than providing a definitive answer as to a single best option. Any limitations in model and data quality will limit LCCA output quality.

Three examples of life cycle cost analysis of civil infrastructure construction projects are provided below. In the first example, a bridge deck life-cycle cost analysis by Berke used STADIUM® software to compare total costs (NPV i.e., net present value) of plain steel, microcomposite steel, epoxy-coated steel, galvanized steel, and stainless steel rebar on a bridge deck that crosses the Ohio River (Berke, 2012). Though only the microcomposite and stainless steels were actually capable of providing the 100-year service life (required by the study) without substantial repair needs, the results (Table 2) provide significant insight as to how factors other than initial cost (e.g., long-term maintenance and repair costs) can influence materials selection.

Table 2.—Results of bridge deck LCCA

| REBAR Material / TYPE | Estimated time to corrosion initiation [years] | Estimated time to first repair [years] | Initial Cost, Rebar [$ / ft ² conc surf area] | Repair Cost, First Repair (NPV) [$ / ft ² conc surf area] | Total Cost (NPV) [$ / ft ² conc surf area] |
|---|---|---|---|---|---|
| Plain Steel | 19 | 26 | 8.16 | 5.62 | 20.14 |
| Stainless Steel (avg) | >100 | >100 | 27.66 | 0 | 27.66 |
| Microsomposite Steel (avg) | >100 | >100 | 11.44 | 0 | 11.44 |
| Galvanized | 59 | 76 | 13.68 | 0.76 | 14.86 |
| Epoxy-Coated | 19 | 34 | 9.36 | 3.95 | 17.79 |

**NOTES**

1. The analytical model included deicing salt exposure and 1.5-inch concrete cover in all cases.
2. Repair expenses were assumed to be repeated at 15-year intervals after first repair. (Repair Cost: $150/ft$^2$)
3. Net Present Values (NPV) assumed a 4% discount rate.
4. Reported value for stainless steel is the average of values for two different grades.
5. Reported value for microcomposite steel is the average of values for three different grades.

In the second example, Moruza compared epoxy-coated rebar (ECR) and microcomposite steel rebar using construction costs based on historical VDOT records. He found that the use of ECR offered an initial cost advantage but that this advantage was diminished by both the higher cost of deck-sealing operations necessitated by the use of ECR and the indirect costs to road users (which effectively quadrupled the life cycle cost of ECR). He found that microcomposite steel rebar would not only cost less but would be more capable of accommodating the demands of expected traffic growth (Moruza, 2010 [MMFX2 doc]).

In the third example, Kahl performed a basic LCCA using Bridge LCC 2.0® for two rehabilitation strategies for a bridge deck. (Kahl, 2012). The analysis period was 100 years. Kahl used a 60-year expected service life for ECR (based on MDOT forecasts) and a 100-year service life for stainless steel (based on estimates in published literature). Results indicated (Table 3) that the equivalent uniform annual cost (EUAC; given a 4% discount rate) of epoxy-coated rebar was higher than that of a combination of solid stainless steel and stainless steel-clad rebar despite its significantly lower initial material cost.

Table 3.—Equivalent uniform annual cost (EUAC) of two bridge deck reinforcement alternatives

| **REBAR Material / TYPE** | Initial Cost, Rebar [$ / lb] | Initial Cost, Construction [$] | Rehabilitation Recurrence (Service Life) [years] | Rehabilitation Cost [$] | Indirect Cost [$] | Lifecycle Cost [$] | EUAC [$] |
|---|---|---|---|---|---|---|---|
| Stainless Steel + Stainless Clad | 3.21 | 3,947,690 | 100 | 271,000 | 121,000 | 4,219,000 | 45,350 |
| Epoxy-Coated | 1.00 | 3,587,016 | 60 | 1,004,000 | 432,000 | 4,591,000 | 49,350 |

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