MITIGATION OF CORROSION IN CONCRETE BRIDGES

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Background

The deterioration of various concrete bridge components built in the past with black steel reinforcement is one of the most common, most damaging and most costly problems facing bridge owners in the United States. The major cause of concrete deterioration (cracking, delamination, and spalling), is the corrosion of embedded black steel reinforcing bars as a result of chloride ions (permeating through the concrete cover) in combination with moisture and oxygen. The average black steel reinforced concrete (R/C) bridge deck, in a snow belt State, showed spalling in about 7-10 years. Although prestressed concrete (PS/C) bridge members are generally cast with good control of mix designs and curing regimes, they are still vulnerable to corrosion (of the pretensioned, uncoated strands) similar to that of the black steel in reinforced concrete, albeit after a longer period of service. Since PS/C members rely on the tensile strength of the strands to resist loads, loss of a few strands per member could be catastrophic. Even small corrosion pits cause fracture of a strand, as compared to non-prestressed concrete reinforcing that will literally rust away without breaking.

For post-tensioned concrete (PT/C) bridge members (both external and internal prestressing), the voids in grouted ducts and/or excessive bleed water (in certain grout mix designs), in addition to chloride/water entering the rough breached ducts or faulty joints at anchorage locations, will corrode the uncoated strands. The underlying difficulty is that there are no reliable, rapid and cost-effective non-destructive methods to assure owners that completed PT/C structures have met the construction specifications. One of the major inspection concerns is whether the ducts in PT/C members have been completely filled with grout and whether there is a uniform coverage over the prestressing steel.

Figure 1. Corroded Strands

Many times, it has been found invariably that the ducts have large voided sections and were only filled partially with grout. In addition, it is very difficult to assess the condition of anchorage areas. Past research has identified that excessive bleed water in certain commercial grouts corroded the strands in a very short time, and that in due time under load, these corroded strands can break prematurely. Since PS/C members rely on the tensile strength of the strand to resist loads, loss of a few strands in members could be catastrophic. Even small pits lead to fracture of a strand, as compared to R/C concrete where the reinforcing will literally rust away (if preventative measures are not taken) without breaking.

This paper summarizes the status of various corrosion protection systems in use for construction and rehabilitation with advantages, limitations, issues and concerns for their use to provide cost effective solutions in controlling corrosion in concrete bridges in the United States.

Corrosion of Bridges in the United States

Corrosion of reinforcing bars and prestressing tendons is one of the most significant and unremitting factors in the process of deterioration of bridges. Of approximately 478,336 bridges (not including tunnels and culverts) in the United States, about 78, 609 bridges are rated structurally deficient. Corrosion is the underlying cause of many of these bridges being rated deficient and many more bridges are showing signs of imminently serious corrosion. In combination with water and oxygen, the main ingredient for corrosion is chloride ions from applications of deicing salts in the snow belt region or marine exposure of concrete bridge members. Chloride ions eventually penetrate the concrete cover, react with embedded reinforcement to form expansive corrosion products, causeing concrete to crack with eventual concrete spalling due to debonding of concrete accelerated by traffic induced vibrations.

Figure 1. Corrosion Damage to Concrete Bridge Pier

While there is a downward trend in the percentage of structurally deficient bridges, the costs to replace aging bridges increased by 12 percent over a recent 5 year period. In addition, there has been a significant increase in the required maintenance of the aging bridges. Although the vast majority of the approximately 108,000 prestressed concrete bridges have been built since 1960, many of these bridges will require maintenance in the next 10 to 30 years. Therefore, significant maintenance, repair, rehabilitation, and replacement activities for the nation's highway bridge infrastructure are foreseen over the next few decades before current construction practices begin to reverse the trend.

A recent study has determined that the total cost of corrosion in the United States alone is approximately $276 billion/year. This figure represents about 3.1 percent of the Gross National Product (GNP) based on 1998 figures. The dollar impact of corrosion on highway bridges is considerable. The annual direct cost of corrosion for highway bridges is estimated to be $6.43 billion to $10.15 billion, consisting of $3.79 billion to replace structurally deficient bridges over the next 10 years, $1.07 billion to $2.93 billion for maintenance and cost of capital for concrete bridge decks, $1.07 billion to $2.93 billion for maintenance and cost of capital for concrete substructures and superstructures (minus decks), and $0.50 billion for the maintenance painting cost for steel bridges. This gives us an average annual cost of corrosion of $8.29 billion. Life-cycle analysis estimates indirect costs to the user due to traffic delays and lost productivity at more than 10 times the direct cost of corrosion. In addition, it was estimated that employing "best maintenance practices" versus "average practices" could save 46 percent of the annual corrosion cost of a bridge deck reinforced with black steel bars, or $2,000 per bridge per year.

Following is a synopsis of various corrosion protection systems for construction of new concrete bridges and rehabilitation of existing salt-contaminated bridge members.

Corrosion Protection Systems for Construction of Concrete Bridges

Epoxy Coated Reinforcing Bars (ECR)

Epoxy coating for reinforcing bars is a barrier system, developed by FHWA in 1974, for the purpose of preventing chloride ions from reaching the surface of the black steel bars. To date, ECR has been used in approximately 100,000 structures including 20,000 highway bridges. Total accumulated usage of ECR is about 4.5 million tons and there are 35 coating plants in North America.

At this time, all States (except Florida) use this system extensively. In general, epoxy coated reinforcing bars have shown excellent performance in bridge decks. Excessive defects, bare area and holidays will compromise ECR's good performance. Experience indicates that prefabrication of bars should be done first and then the coating applied- better performance will result due to avoidance of bending stresses in the coating. ECR top bar mats should not be coupled with a large uncoated cathode, such as a black steel bottom bar mat to avoid macro-cell corrosion currents. ECR reinforcing used in situations involving excessive moisture, salt and high temperatures, marine exposure, highly permeable concrete, cracks, etc. are prone to premature failure. In these situations, a reduction in adhesion of epoxy to reinforcing bars has been observed in concrete with or without chloride ions. Long-term corrosion performance of ECRs in concrete cannot be guaranteed on the basis of increased adhesion evaluated by available laboratory screening tests. Accelerated laboratory tests for adhesion (cathodic disbondment, hot water immersion in varying pH and salt) are not the best indicators for ECR performance in concrete.

Epoxy coated reinforcing bars have proven to be a cost-effective corrosion protection system for bridge decks, especially when both the top and bottom mats are coated. The premium cost of epoxy coated steel versus uncoated black steel is about 20%. However, the total cost increase on a typical bridge structure is in the range of 1 to 2%. In the United States, the estimated potential savings in bridge deck costs due to ECR use (with projected twice the corrosion-free service life for bridge decks already constructed with ECR instead of black steel) is in the $5 to $10 billion range.

Solid Stainless Steel Reinforcing Bars

Solid stainless steel reinforcing bars experience corrosion rates of up to 100 times less than black steel and show excellent performance in laboratory in both accelerated corrosion tests and long-term performance in concrete specimens. No macro-cell current can be detected between a stainless anode and a black steel cathode in a salt contaminated reinforced concrete slab. The 316 grade of stainless steel exhibits better performance than the 304 grade steel. The high cost of solid stainless steel bars - around $2 to $3 per pound compared to 15 cents/pound for black steel – can be prohibitive because total structure costs may increase by up to15 to 20 percent versus a structure reinforced with black steel. The process of fabricating bar deformations by welding wire on smooth reinforcing bars has reduced the price by 20 percent. Evaluation of this process is underway compared to normal rolled down stainless reinforcing bar in conventional steel mills, but the supplier of this product from the United Kingdom is currently out of business. Structures reinforced with solid stainless steel reinforcing bars can be expected to provide a maintenance-free service life of greater than 75 years. In the US, there are a few states, namely Virginia, Oregon, New Jersey, Michigan and Montana, using solid stainless steel reinforcing bars on an experimental basis. The high costs for this system can be justified for strategic bridges due to lost man-hours caused by detours and environmental concerns with high traffic density. A good example is the bridge crossing the Middle Fork of the Flathead River on US Route 2 near Essex, Montana. One end of the bridge terminates in Glacier National Park and the other at Flathead National Forest. Heavy snow, frequent salt applications and freeze-thaw cycles result in a harsh environment and any closure of the bridge involves a detour of 300 miles.

Figure 2 a. US Route 2 with Stainless Steel Bars

Figure 2 b. Stainless Bars & Chairs

Stainless-clad Reinforcing bars

A promising alternative to the high cost of solid stainless steel reinforcing bars is bars with a stainless steel cladding on the surface. The estimated production cost of 60-75 cents per pound compare very favorably to the $2 to $3 per pound for solid stainless steel bars and is just four times the cost of black steel (resulting in a total structure cost increase of about 5 percent). Stainless-clad reinforcing bars have exhibited excellent performance in accelerated laboratory tests. Issues related to fabrication include: protection of bare cut ends - welding a stainless steel cap on the cut end or stainless metal spray is under evaluation; and deformation and bendability at present may not be as good as that of solids bars. The long-term physical properties and performance of the core steel and the cladding is a concern in the two currently competing processes for manufacturing clad bars – Nuovinox and plasma coated. About 10 to12 field installations are planned by various states in the United States. Early results of laboratory testing indicate a bright future if the price can be held at the present level.

Corrosion Inhibitors

Corrosion inhibitors, generally mixed in with the water during concrete mixing, present an alternative to epoxy coated reinforcing bars at roughly comparable costs. Performance of inhibitors has been shown to be variable due to varying chemical composition - some are better than others. Basic inhibitor types include anodic, cathodic and mixed (or organic). At this time, calcium nitrite is the only corrosion inhibitor that has shown promise to combat corrosion. Equal amounts of nitrite ions are required in the concrete to counteract the corrosion caused by same amount of chloride ions. For good performance, expected chloride ions at reinforcing bar level for the total design service life should not exceed available nitrite ions. With time, nitrite ions redistribute towards the bottom of concrete slab and eventually can leach out after long-term service exposure. Corrosion inhibitors are more commonly used in prestressed concrete members due to non-use of coated strands. Corrosion inhibitors are not considered effective for rehabilitation of salt-contaminated structures because there is no efficient system capable of delivering the inhibitor ions to the reinforcing bar level thru hardened concrete. In a marine environment (continuous high salt, moisture and temperature), the use of corrosion inhibitors in conjunction with epoxy coated reinforcing bars is recommended as an effective corrosion protection system.

High Performance Concrete

High quality ("High Performance") concrete is the primary corrosion protection system for any concrete structure or element. It is the first defense against intrusion of chloride ions and also to provide high alkalinity for a passive environment for the reinforcement. High quality concrete should have a low w/c ratio, low permeability, be crack-free and provide adequate cover over the reinforcing bars. Most bridge owners in the US employ proven additives such as fly ash, silica fume, polymers, epoxies, or latex modifiers to reduce concrete permeability. These admixtures should be used in optimal amounts so as to not reduce the pH of the hardened concrete. The majority of states are now developing and specifying high performance concrete mix designs and procedures for use in the field to construct bridges with fewer members or slender design at low cost as well as for basic corrosion protection. In one current example of high quality concrete as a protection system, the State of Florida mostly relies on the use high quality concrete with good cover alone for corrosion protection of their bridges located in a marine environment. At present, corrosion inhibitors, stainless steel and clad reinforcing bar, etc. are being used experimentally on a few projects. The Florida Department of Transportation has experienced premature corrosion with ECR in marine environments and they do not use ECR while they continue to evaluate corrosion resistant reinforcing alloys that would perform better than ECR.

Rehabilitation Systems for Concrete Bridges

Cathodic Protection (CP)

In the past several decades the FHWA has developed a number of impressed-current, cathodic protection (CP) systems for concrete bridges and approximately five hundred bridges in the United States are currently protected by CP systems – the State of Missouri alone has installed CP on about 200 bridges. The FHWA initially developed a conductive polymer anode for slotted and mounded CP systems. Currently, titanium mesh anode covered with an overlay is a standard impressed CP system for horizontal surfaces, (e.g., bridge decks). The cost of CP installations is reasonable at $6 to 8 per square foot ($0.56 to $0.75 per square meter) of concrete surface but CP systems are being used more in parking garages than on the bridges.

Impressed current CP systems require maintenance of rectifiers and other electrical circuits for them to function. If an impressed-current CP system is not properly functioning and polarizing the steel adequately, the structure is not protected and corrosion can continue. Maintenance is a significant problem for impressed CP systems. The FHWA has now developed tow maintenance-free galvanic CP systems for substructure bridge members and the states of Florida and Oregon are leaders in developing and installing galvanic CP technology for their bridges. Three galvanic anode systems, zinc-hydrogel, zinc-Indium-Aluminum alloy, and zinc alone or with humetants are in use today for inland vertical and upside bridge members away from the water. Galvanic CP systems have broader appeal to the State DOT's with their limited personnel resources and minimal maintenance requirements. For PS/C, tendon to concrete bond is only reduced slightly for charge transfer equal to 160 years of CP. For PS/C, hydrogen embrittlement is not an issue when polarization is maintained below -0.90v (SCE) and there is a methodology available for qualifying PS/S members for CP. Normally, galvanic anodes are a more suitable choice for PS/C in avoiding accidental hydrogen embrittlement of high strength steel strands because they deliver low currents at low voltages.

Electrochemical Chloride Extraction (ECE)

Another method of protecting concrete elements from chloride induced corrosion is to move the chloride ions away from the location of the reinforcing steel. This can be done via a procedure known as electrochemical chloride extraction, which in principle is simply an accelerated cathodic protection process. The reinforcing steel in the concrete bridge member (pier column, deck, etc.) is the cathode; a temporary anode is anchored to the outer surface of concrete in an electrolytic solution and a current (0.1 to 0.2 amps per square foot of concrete surface) is applied from a direct current power source. This current is 100-200 times higher than that for cathodic protection and the process is applicable to reinforced concrete only. The procedure takes approximately 4 weeks. The chloride ions move outwards and sodium ions inwards toward the reinforcing bars to eliminate corrosion. In general, the concrete surface is either coated with sealers (substructure) or overlaid with concrete (decks) after chloride removal to inhibit the penetration of future chloride ions.

This technology was tested for more than 25 years ago by FHWA at Kansas DOT and Battelle Institute. A number of states have now used this technology and the costs are reasonable. No maintenance is required after completion of the process. The costs of ECE are comparable to use of a CP system, but long-term performance of the process in protecting the concrete member treated with ECE is not yet well known. More research is underway to define criterion for process completion with some assurance of desired corrosion-free service life.

Conventional Methods - Overlays, Sealers and Patching

The majority of bridge owners still prefer and depend on conventional methods over electrical methods such as cathodic protection and electro-chemical chloride extraction process. Low permeability concrete overlays have been shown to extend the life of bridges by 15-30 years. Latex-modified concrete, silica-fume concrete, low water - cement ratio concrete and polymer concrete are the most commonly used overlays to slow down the future ingress of chloride ions. This rehabilitation methodology requires no maintenance after installation, but corrosion continues since chloride still resides at the reinforcement level. After overlay installation, the corrosion rate somewhat decreases with passage of time due to drying of concrete at reinforcing bar level and the lesser availability of future ingress of chloride ions. The cost of a low permeability overlay at $5 to $10 per square foot ($0.46 to $0.93 per square meter) is reasonable, but it does not stop the corrosion process completely.

Conclusions

Corrosion is an inescapable process, since all processed construction materials eventually revert back to their natural form. The FHWA has made much progress in the area of new bridge construction for the last 25 years. The corrosion protection systems that are in use today are performing satisfactorily. More needs to be done in developing corrosion resistant reinforcements and other corrosion protection systems such as corrosion inhibitors and more durable concrete mix designs. Since all materials will eventually degrade, in the future we have to find ways to rehabilitate the so-called corrosion-resistant bridges of today with improved cost-effective methods and technologies. At present, there are 250,000 bridges, which contain black steel and will need rehabilitation in the future. The present challenge is to make CP, chloride removal, and other processes cost-effective for bridge owners to use. Corrosion engineers and scientists will always play major roles in the development of corrosion-resistant materials for more durable new bridges as well as to find more cost-effective methodologies for extending the life of existing bridges.