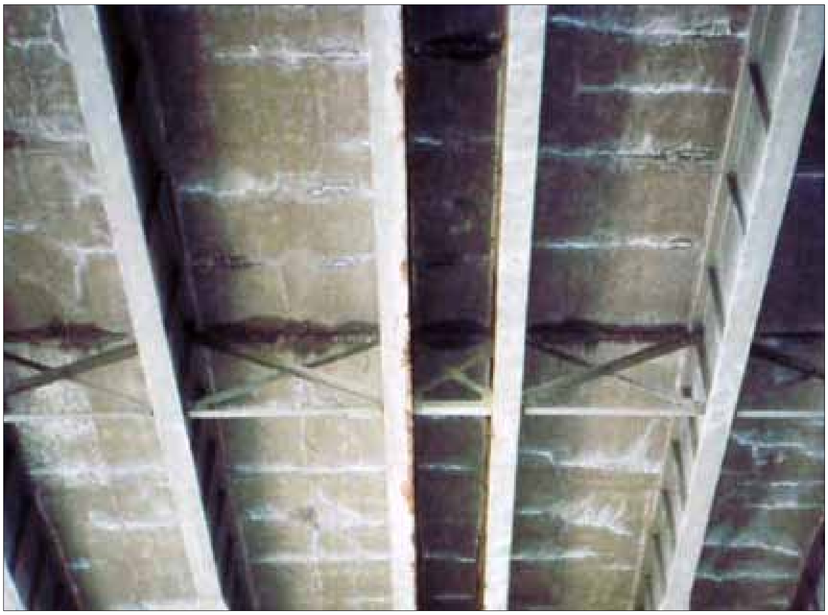
By Tom Kuennen, Contributing Editor



Transverse deck cracking *complicated by HPC, such as this in New York State seen from underside, has diminished enthusiasm for HPC in bridge decks as a corrosion protection method.*

Photo courtesy of Paul Krauss

Research continues to produce new options for owners and designers to save concrete bridges.

Corrosion! The Enemy Within

If water is the enemy of pavements, then corrosion is the bane of bridges.

Corrosion of reinforcing steel in concrete bridges degrades bridge decks and other superstructure elements – in addition to substructures – by causing embedded steel to expand, causing cracks in concrete, leading to rough riding surfaces at best, and structural failure at worst.

Fortunately, many tools exist in the bridge owner's "toolbox" of fixes to slow or halt corrosion in its tracks. Corrosion prevention can be built into a bridge or applied retroactively. Pavement deicing techniques and materials also can moderate chloride-induced corrosion.

Research continues to produce new options for the owner and designer to consider. Here's a look at some of those changes and options.

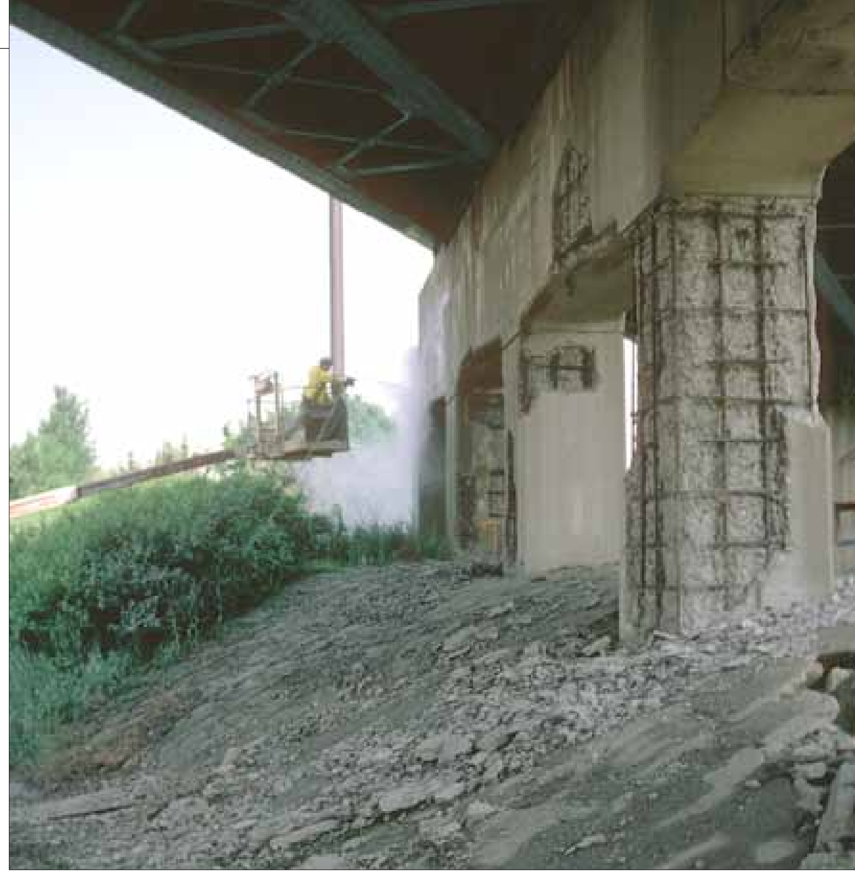
Bridge corrosion results from the reaction between the steel and its environment. Steel is refined from iron ore, but the moment it is produced it begins to corrode, primarily to oxide compounds, on its way to a less-refined state.

Steel bridges can also suffer greatly from corrosion, and they usually are well protected by a variety of high-performance bridge coatings. But in recent decades, the proliferation of steel-reinforced concrete bridges – constructed of prestressed or post-tensioned elements including girders, piers, pier caps and decks – has focused a tremendous amount of attention on preventing corrosion of steel within concrete.

Because portland cement is highly alkaline, concrete made from it provides a layer that offers passive protection to the steel within. Reinforcing steel develops an initial oxide film on its surface from an initial corrosion, and concrete's high alkalinity stabilizes the film. But because PCC permits movement of liquids through its pores, microcracks and cracks, chloride-laden meltwater from snow and ice, or marine spray in littoral environments, can reach the steel within, disrupt the oxide film, and accelerate corrosion.

Not only is the steel degraded by the chlorides, but because the products of corrosion take up more room than the existing steel, tremendous outward pressures induced by the chemical reaction crack the concrete, resulting in more cracks that let more chlorides into the concrete, accelerating the process. The outward manifestation can be cracks with rust stains seeping out onto the concrete surface, or spalling and delamination of concrete with structural degradation.

Deicing and marine salt water is not the only culprit; corrosion of reinforcing steel also can take place via concrete carbonation, a reaction with free atmospheric carbon dioxide, which lowers the pH of the concrete. This extremely slow process reduces the ability of the concrete to protect embedded steel.



***If not controlled**, deicer-induced corrosion can result in spalling that can degrade a bridge substructure, here being cleaned prior to repair.*

Photo courtesy of Tom Kuennen

A toolbox of fixes

The toolbox of corrosion fixes available to protect reinforced concrete bridges by both passive and active means is wide ranging, and continually changing. These fixes include:

- **Enhanced Reinforcement.** Steel rebar may be epoxy-coated, galvanized or clad in inert stainless steel to resist corrosion. The rebar itself may be of stainless steel, or, more recently, a carbon fiber polymer composite that will not corrode.
- **Concrete Additives and Mix Designs.** Admixtures such as microsilica (silica fume) fill up the pores of the concrete, inhibiting migration of chloride-laden water. Low water-to-cement mix ratios help. And high-performance concretes (HPC) — which resist migration of chlorides in addition to boosting concrete compressive strength — have been used with some success, although unanticipated deck cracking linked to HPC has caused designers to rethink HPC in bridge decks in recent years.
- **Surface Sealers and Membranes.** Largely impermeable dense and microsilica-enhanced concrete overlays, silane/siloxane sealers, methacrylate resin crack sealants, latex modified concrete overlays, and waterproof deck membranes keep superstructures protected from damaging chlorides.
- **Electrochemical Fixes.** These include active cathodic protection of bridge structures and the removal of chlorides from them.
- **Maintenance Best Practices.** Use of more expensive noncorrosive deicers, continuing repair of cracks, washing of decks, and periodic upkeep of drainage and bridge joints go a long way to protecting a bridge from corrosion.

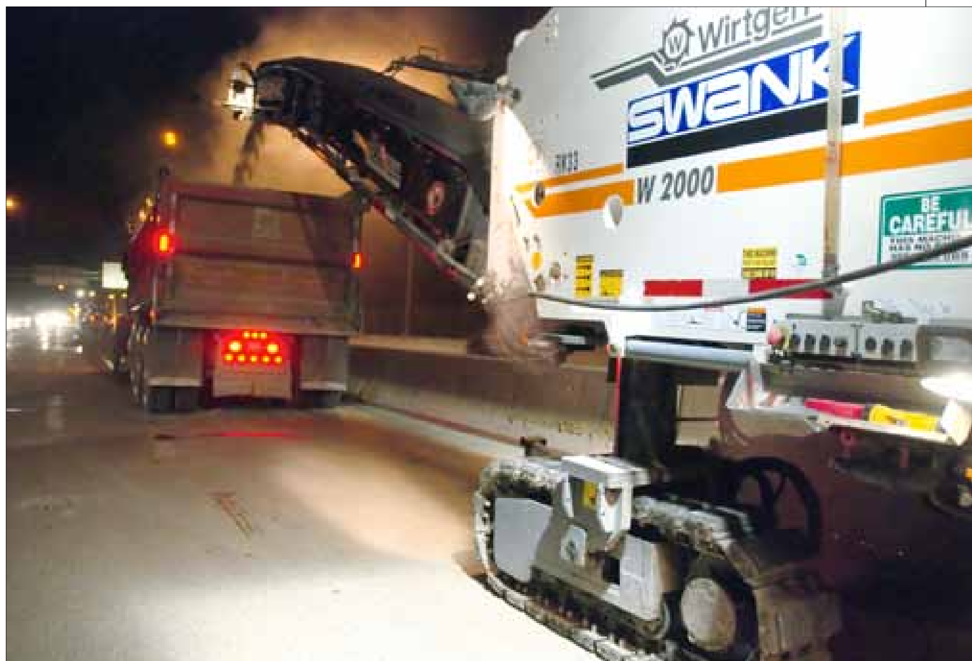
Getting the deck right

"The principal mechanisms of bridge deck failure are surface deterioration and corrosion of the reinforcing steel, due to chloride ion intrusion," write William S. Caires, principal, and Stanley R. Peters, P.E., senior engineer, for Centennial, Colo.-based Construction Technical Services, in their 2006 report to the Colorado Department of Transportation, *Evaluation of Products that Protect Concrete and Reinforcing Steel of Bridge Decks from Winter Maintenance Materials*.

If that's true, then a robustly resistant deck surface provides the first line of defense against chloride penetration. A resistant deck will inhibit rapid chloride penetration and resist penetration from ponded meltwater over longer periods. But it also will have to be abrasion resistant, Caires and Peters write.

"Concrete mixes need to be developed to minimize drying shrinkage and permeability (high density, low shrinkage) as a second line of defense against chloride intrusion," they say. "However, membranes appear to be the

>>>



***After decades of service**, tough latex-modified concrete bridge deck overlay is milled with great effort on I-376 in Pittsburgh on a Friday night; new LMC overlay would be placed the next day and bridge reopened by rush hour Monday morning.*

Photo courtesy of Wirtgen America, Inc.

most effective method of preventing the direct intrusion of deicing chemicals through cracks that always occur."

A popular deck barrier to deicers is a latex modified concrete (LMC) overlay. It's used on busy highways as well to stand up to traffic. But LMC more often is placed as a thin bonded overlay on bridge decks and parking structures.

> **LMC has been used for a lot of years, and there are a lot of decks that have had very good success, for example, in Chicago. But other agencies have had early-age plastic shrinkage crack problems.**
>
> — Paul D. Krauss, P.E., principal of Northbrook, Ill.-based Wiss, Janney, Elstner Associates, Inc.

As LMC cures, the polymer forms internal plastic films which result in low permeability to chlorides, low modulus of elasticity (making it more flexible than conventional concrete), a bond that's stronger than the substrate below, and high durability against abusive traffic loads. However, eventually LMC overlays will have to be replaced, and as strong as they are, they pose an exceptional challenge to contractors who will have to mill the aged LMC overlay in advance of a replacement.

"Latex modifiers help in the adhesion of the overlay to the deck, and also help reduce the permeability of the concrete," says Paul D. Krauss, P.E., principal of Northbrook, Ill.-based Wiss, Janney, Elstner Associates, Inc. "LMC has been used for a lot of years, and there are a lot of decks that have had very good success, for example, in Chicago. But other agencies have had early-age plastic shrinkage crack problems."

Another option, penetrating silane/siloxane sealers, travel deep into the concrete deck, forming a chemical bond with the concrete, and repelling water.

Another permutation is the *SafeLane* ice prevention overlay from Cargill. The 3/8-inch thick overlay is constructed with epoxy and broadcast aggregates like typical multiple layer epoxy overlays that are used to provide a skid-resistant wearing and protective surface for bridge decks, reports Michael M. Sprinkel, P.E., of the Virginia Transportation Research Council.

The aggregates used in the overlay differ in that they are said to absorb and store liquid deicing chemicals that are applied to the surface. "These chemicals have the potential to reduce, and in some situations prevent, the accumulation of ice and snow on the overlay and thereby reduce the number of snow- and ice-related accidents," Sprinkel says.

Backing away from HPC

High-performance concrete is durable concrete because its strength and impermeability to chloride penetration makes it last much longer than conventional PCC. It's an engineered concrete made up of the classic elements of water, portland cement and fine and coarse aggregates, but with added components.

In HPC, materials and admixtures are carefully selected and proportioned ("optimized") to form high early strengths, high ultimate strengths and high durability beyond conventional concrete.

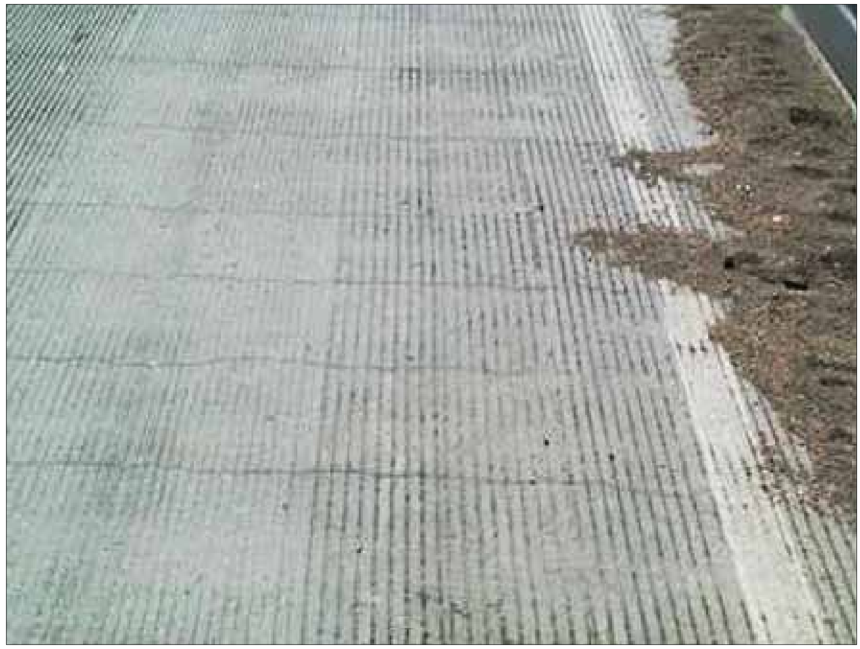
HPC provides enhanced mechanical properties in precast concrete structural elements, including higher tensile and compressive strengths, and heightened modulus of elasticity (stiffness). In frost-prone regions the benefits of HPC are great. The enhanced durability of HPC helps it resist penetration of chloride-laden snow and ice meltwater. This results in longer life for the reinforcing steel within, and a reduction in spalling, cracking and associated repairs.

The Strategic Highway Research Program (SHRP, 1987-1993) studied the efficacy of HPC in bridge structures as a way to quell corrosion of rebar from meltwater from deicing salt. The first HPC structural designs were constructed in the mid-1990s. HPC began migrating to pavements in the late 1990s, and in 2004 it had fully penetrated PCC pavement construction.

HPC durability criteria include air void structure, low permeability, proper water

>>>

content of fresh concrete, and low susceptibility to cracking. Some industrial "waste" materials of a few decades ago now are integral elements of this new engineered concrete. These admixtures, such as coal fly ash, microsilica and ground granulated blast furnace (GGBF) slag, add both strength and durability to the concrete, and enhance its marketability as an environmentally friendly product.



▲ ***Transverse cracks** in Colorado HPC deck*

Photo courtesy of Paul Krauss

The problem of early cracking

While HPC continues to be used in bridge superstructures, substructures, and in high-rise buildings, it's fallen into disfavor for bridge decks due to unanticipated early cracking.

Early cracking in concrete bridge decks is a complex issue, and probably results from a combination of production and placement factors, such as high evaporation rate, high magnitude of shrinkage, the use of high slump concrete and excessive water in the concrete during mixing or placement, insufficient top reinforcement cover, insufficient vibration of the concrete, inadequate reinforcing details at joints, and the weight and deflection of the forms, according to researchers for the Kentucky Transportation Cabinet (the state's DOT).

The alarm first was sounded in National Cooperative Highway Research Program (NCHRP) Report 380, *Transverse Cracking in Newly Constructed Bridge Decks*, by Krauss and Ernest Rogalla, S.E., both of Wiss, Janney, Elstner Associates, Inc., Northbrook, Ill.

Since then, complaints about cracking involving HPC decks have been abundant and widespread, although not all HPC decks have been troubled. In 2004 the Federal Highway Administration released a list of what 23 states were doing to address cracking in HPC bridge decks. The report concluded that careful curing is the secret to trouble-free HPC decks.

"One of the biggest problems that states are fighting right now is that almost all of these high-performance concretes have cracking issues," Krauss said. "California, Illinois and a lot of other states are trying to figure out why their decks crack so much. As far as decks are concerned they haven't had a lot of success preventing them from cracking because they are so strong and tend to be brittle. The cracking problem defeats the purpose of using the HPC."

The increased risk of HPC early cracking is likely related to use of silica fume and their higher strengths, Krauss said. "High strength will make deck transverse cracking even worse," Krauss said. "If one of the aspects of specifying HPC is increased durability, then one of the considerations for durability should be elimination of cracking. It's not all just about permeability; it's about balancing the permeability with workability, how well the concrete consolidates, how consistent will it be for the contractor. All these factors should go into considering HPC for a deck, not just its high strength."

Krauss has researched the efficacy of sealing cracked HPC decks with high molecular weight methacrylate resin. "It's an acrylic resin used as a topical treatment to flood the deck surface and seal the cracks," Krauss told *Better Roads*. "If cracks occur in a bridge deck, we know the cracks will reduce the performance of that deck. The resin flows down into the cracks and bonds and seals them."

Such cracks can be very hard to see on the top of the deck, due to its textured surface and grooves, which is a reason to spread the resin across the deck. "They're hard to see and hard to follow," Krauss said. "They will be more evident from the bottom of the deck due to water staining. When you have so many of these cracks, it doesn't make much sense to chase each individual crack; it's easier just to coat the whole surface."

If an impervious deck is the first line of defense against chloride-induced corrosion, the last line will be coatings that keep the deicers off the rebar itself, and the most popular option there is epoxy coated reinforcing steel.

Epoxy coated rebar has become very widely used in recent decades. When it first appeared in the early 1970s, epoxy coating added 80 percent to 120 percent to the cost of uncoated reinforcement, according to the Concrete Steel Reinforcing Institute. But since then, the cost of epoxy-coated reinforcement has dropped significantly, CRSI says, especially when life cycle costs are calculated, including the avoidance of corrosion-induced cracks, spalls and potholes.

"There is definitely a lot of value in epoxy coating of rebar, especially for the price," Krauss said. "The research and field performance has proven it to be an effective method of reducing corrosion of reinforcing steel." The benefits? One of the major benefits, Krauss said, is that the rebar is being protected from chlorides, and at the same time, electrically isolating the bars from each other. "This dramatically reduces the corrosion rate over time," Krauss said.

One way of avoiding the corrosion problem altogether is to use inert nonmetallic reinforcement that won't corrode. Stainless steel rebar is another long-standing but expensive option. A less-expensive option ultimately may develop from the new generation of carbon fiber reinforced polymer (CFRP) bars that continue to undergo analysis in the lab and in the field.

In 2006 the Kentucky Transportation Cabinet released the report, *Inspection and Evaluation of a Bridge Deck Reinforced with Carbon Fiber Reinforced Polymer Bars*, by Choo Ching Chiaw and Issam E. Harik of the Kentucky Transportation Center at the University of Kentucky, which said that the cracks in the CFRP decks it studied were well below the accepted threshold.

In a bridge, CFRP bars were employed as transverse and longitudinal reinforcement in the top and bottom reinforcing mats. The bridge was opened to traffic in May 2002, with monitoring of crack formation and location, and maximum crack width and length in the deck begun the next month, and continued until September 2005. "The cracks in the deck were not measurable since the maximum observed crack width was less than the smallest measure of 1/100 in. on the crack comparator," the authors write. "This indicates that the cracks are well below the maximum allowed crack width of 0.013 inch per AASHTO Standard Specification for exterior exposure."

>>>

Facing the dilemma of cathodic protection

While there are many means of protecting steel from corrosion, there is only one certain way to actually stop it from happening, and that's cathodic protection (CP).

CP eliminates corrosion by making the reinforcing steel a cathode via an impressed direct current (DC), or by connecting it to a sacrificial or galvanic anode. The applied current counteracts the electrical charge released in the corrosion reaction, stopping the corrosion in its tracks.

The problem is, cathodic protection requires attention, and if they are not absolutely required to do so, engineers and owners are loathe to specify materials or processes that require monitoring. "Set and forget" are the bywords.

"Cathodic protection for bridges really hasn't taken off," WJE's Krauss told *Better Roads*. "It's still here, but it isn't widely accepted."

Research into cathodic protection for bridge decks dates to work done by Richard Stratfull of Caltrans, beginning in 1959. "He was responsible for some of the earliest applications of cathodic protection for concrete decks, and there have been a lot of other systems put in place since then," Krauss said. "But they haven't really taken off as a common thing to do, partly because of a lack of awareness on the part of the state DOTs, but also due to the maintenance required of the system.

"A lot of the systems work for a couple of years, and if no one goes out to maintain them, they can work imperfectly," Krauss said. "It can be too much of a burden for the DOTs to maintain and keep track of them. State agencies that are more aggressive implementing bridge deck cathodic protection usually have a good electrical group with technicians who understand electrical systems."

Krauss has visited existing cathodic protection systems. "Oftentimes they are not well-maintained or are not working," Krauss said. "Individual zones won't be working; different zones may be partially working, while other zones may not be working at all. It becomes a challenge to the owning agency."

***(Top) Methacrylate resin** is spread on bridge deck to seal high-performance concrete-related cracking.*

Photo courtesy of Paul Krauss

***(Bottom) Elgard cathodic protection** mesh on bridge deck is covered with latex-modified concrete overlay.*

Photo courtesy of Virginia Transportation Research Council

This was borne out by a 2008 report by the Virginia Transportation Research Agency. In *Survey of Cathodic Protection Systems on Virginia Bridges* by Michael C. Brown, Ph.D., P.E. and Stephen R. Sharp, Ph.D., research scientists for the Virginia Transportation Research Council, the researchers found that bridge CP systems in the commonwealth were successfully deployed, but not always.

"The Virginia [DOT] has used CP systems on 12 reinforced concrete bridge structures," the authors write. "Although CP systems deployed in concert with VTRC research studies remained in service, the researchers found little evidence that the transfer of the responsibility for maintenance and monitoring of those systems to the appropriate VDOT field personnel has occurred.

As a result, little information has been gathered regarding the performance of these systems beyond the initial evaluations during the research studies. In addition, this led to little or no maintenance of CP systems being conducted at these sites."

VDOT's bridge inspection reports were found to include only minimal information about the status of the systems in place on the structures evaluated in the field survey, they said. "It appears that visual observations have been made about the outward appearance of the systems. However, routine electrical measurements to confirm the operational status of these systems were not reported, thus it is not clear from the records that sufficient cathodic current has been applied to ensure protection of the structure(s). This points to a policy need for consistent routine maintenance and monitoring of CP systems to document their performance."

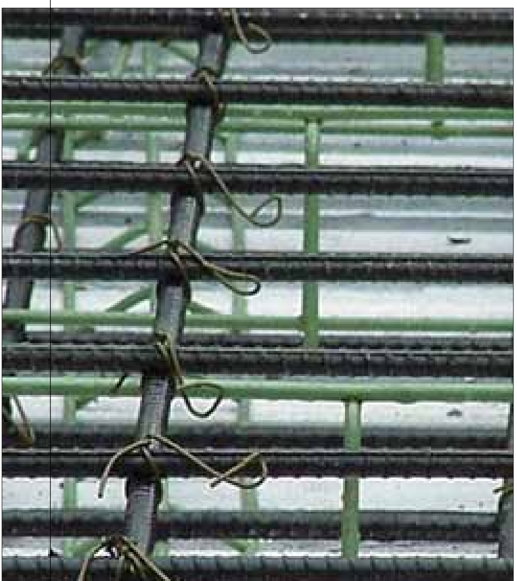
Even if CP systems are working, they will need to be periodically fine-tuned. "Bridge deck cathodic protection systems need to be adjusted," Krauss said. "Bridges change over time, so to be effective, the owner needs to adjust the amount of current being applied over time."

Remote monitoring not a panacea

The advent of cellular phone technology has enabled real-time reporting of the status of active systems in the field, in which a field unit will "dial-in" its status to another system, which logs the status or issues an alert if the system is not performing as specified. But these monitoring systems too can misbehave.

"Remote monitoring systems can pull up a system status on a computer," Krauss said. "The problem is that technology also can be prone to failure or lack of maintenance. It can be done, but it can be at a high expense. As DOTs are strapped for money, for them to put remote monitoring systems in service and maintain them poses the same problems they will have with the cathodic protection system itself. In the

>>>



Nonreactive carbon fiber reinforced polymer bars (black) are placed in bridge deck as part of Kentucky research.

Photo courtesy of Kentucky Transportation Center

future such a system may become more reliable and less expensive, and that may help CP systems become more acceptable."

Physical repair of CP systems can involve wiring repairs, or replacement of anodes. "The systems can be damaged for a variety of reasons," Krauss said. "We have seen birds get into control boxes and build nests. Vandalism is a big issue; vandals see wires and want to rip them out or cut them."

When used, cathodic protection may be favored for more costly structural elements like precast/prestressed girders, and piers and columns, rather than the deck.

"The decks on a lot of bridges are expendable," Krauss said. "They are easily replaced, and concentration of cathodic protection will be on supporting elements that are not replaceable. In those areas there is increased interest in corrosion protection, but instead of going totally with active systems, there is a movement toward passive systems that will require less maintenance than the active systems These can be applied to deck supporting elements like girders, ends-of-beams at joints, and piers and pier caps. Leakage at joints is one of the worst offenders; chloride solution then gets down through the joint and we start to get beam corrosion. It can result in a very expensive fix."

Passive CP systems may include arc sprayed zinc, activated zinc sheets, or discrete anodes. These are often combined with improved joint systems and coatings.

Rehabilitation of deck will most often include sealers or low-permeability overlays, said Krauss. "It is relatively easy to do a deck overlay, which will be less expensive than cathodic protection," he said. "Either active or passive CP options will usually be less expensive than deck replacement, and the hope is that the agency owner will get a long service life out of the structure while avoiding the need for lane closures and disruption of traffic that reconstruction brings." ❖