Significant advances in materials and construction technologies over the past few decades have increased bridge durability. This article describes improvements such as epoxy-coated rebar, high-performance concrete, protection of prestressed and post-tensioned construction, advances in coating technology, and risk mitigation procedures that provide cost-effective increased confidence in bridge construction. Current coating systems are also discussed.

Construction of highway bridges has benefited during the last few decades from significant advances in materials and construction technologies aimed at improving long-term durability. This has come about because of the need for concrete repair (Figures 1 and 2) and the presence of reinforcing steel corrosion that has occurred (Figure 3). The mainstreaming of epoxy-coated rebar for bridge decks and the present move toward institutionalization of high-performance concrete formulations for structural concrete elements has already paid dividends. In spite of these gains, more durable designs are still needed.

The presence of natural airborne salt in coastal environments, coupled with the ubiquitous use of deicing chemicals and the realities of service life requirements now approaching and exceeding 100 years, demands additional solutions that provide significant durability upgrades at minimum additional investment.

The protective coatings industry has undergone a parallel revolutionary change during the same period. Old technology, thin film, high-solvent sealers, and waterproofing treatments have been replaced and surpassed in performance properties with newer, high-durability polymers that promise multipurpose functionality and long life. These materials are now engineered specifically to adhere to and protect concrete substrates from the deleterious effects of water and salt while also providing other desirable properties such as graffiti resistance and enhanced visibility and aesthetics. During the last five years, bridge engineers in many state highway departments have begun to ask with increased frequency for engineered protective coatings. This article outlines the key engineering parameters associated with these materials, and describes the current efforts to develop a materials performance
clearinghouse to serve as a resource for unbiased selection of concrete coating materials for highway bridge structures.

**Modern Concrete Bridge Corrosion Protection Design**

Bridge construction methods of the last 20 years have produced a steel-reinforced concrete bridge inventory with performance properties previously unattainable (Figure 1). Concrete bridge spans are longer and lighter, and more robust geometries are now commonplace because of the use of prestressed and post-tensioned designs. Advances in durability design for these newer structures have focused on implementation of epoxy-coated rebar for the mild steel reinforcement and use of advanced, low water-cement ratio, high pozzolan content concrete formulations to reduce chloride permeability significantly. This belt-and-suspenders approach has paid off by extending the expected lifetime of decks and many structural elements, but these designs still present significant long-term risk relative to durability. This is particularly true for the prestressed girder designs that now dominate the bridge construction industry.

Corrosion protection for prestressing strand still relies primarily on the low permeability of concrete cover for protection of the high load-bearing steel strand. Present corrosion protection designs rely on the assumption of little to no cracking in the low-permeability concrete. Should cracking occur, the high-strength, load-bearing steel strand embedded in prestressed designs carries no secondary corrosion protection. In many design elements, the uncoated high-strength steel strands within prestressed bridges are protected from environmental assaults by only an inch or two of concrete cover, which may or may not crack.

Additionally, current mainstream corrosion protection approaches for prestressed and post-tensioned structures are not inspectable or repairable. Evidence of corrosion deterioration most often shows up in the form of spalling of exterior layers of concrete because of the expansive forces of the corroded steel. Once this level of deterioration has occurred, the options for rehabilitation are limited and costly. These factors impact long-term risk analysis and impede a bridge manager from dealing aggressively and appropriately with any early indications of failure among bridges or bridge elements. The addition of exterior coatings to the bridge manager’s toolbox in a
rational and targeted manner can mitigate some of this existing design-based risk to durability.

**Risk Mitigation**

To date, corrosion engineering decision making has been driven primarily by the trade off between initial and life cycle cost. Corrosion protection technologies such as the use of cathodic protection, more inherently corrosion-resistant structural materials, and durable coating systems exist, but must be chosen and installed at an increased cost during construction. The decision to harden a structure to corrosion most often has required a significant leap of faith for managers with regard to the future deterioration curve of that structure.

Several factors have worked against the up-front investment in corrosion protection technology. First has been a lack of confident deterioration data. We do know that corrosion does exist and will occur in salt- and moisture-laden environments, but we do not usually have definitive answers as to when and at what rate it will occur. This lack of deterioration rate data very often takes the steam out of pure life cycle analysis.

Also, the design life cycle of our structures, in general, has been a moving target. While the vast majority of existing highway bridges was designed to meet a 50-year design life, goals have moved to the right and now discussions focus on 100-plus years for structures designed today. These factors make a life cycle cost calculation somewhat divergent and less confident. For this reason, in recent years corrosion engineers have focused arguments for investment in durability toward more of a risk mitigation approach; that is, investment in technologies that provide an increased confidence in performance at a known, palatable cost relative to the costs of contingencies if the investment is not made.

The cost trade off to be examined going forward should focus less on the spectrum of life cycle vs. initial cost, and more toward the value of up-front investment to mitigate the risk of unscheduled repair, system downtime, and ultimately bridge failure and replacement. This examination has led several agencies to add investment up front in order to extend projected life from 50 to 75 to 100 years or longer. Examples of this new approach can be found in the use of high-durability, plural-component coatings for the exterior protection of structural elements of the new lanes of the San Mateo Bridge in California by Caltrans, and in the mandate for coatings for beam ends under exposed joints for all bridges in Wisconsin. Other states using a similar approach targeting beam ends include Florida, New Jersey, and the District of Columbia.

In the Caltrans case, an approximate $10 million investment was made in the “extra” coating system in order to meet an extended life requirement of 125 years for the $190 million structure. This represents an initial investment of ~5% to achieve an additional projected 25 years of service life for this critical structure. At the other end of the spectrum, targeted applications such as the beam ends for Wisconsin’s bridges should be expected to add only a few dollars per square foot while imparting a significant reduction in risk to the most vulnerable portions of the structure.

In both of these contrasting cases, the corrosion protection system continues to be visible for inspection and accessible for maintenance throughout the lifetime of the structure. This provides the opportunity for truly preventive maintenance to be performed at a fraction of the cost expected due to structural repairs initiated by internal steel corrosion.

**Modern Concrete Coating Technologies**

Most civil engineers are familiar with basic concrete waterproofing and sealer type coating materials, and these materials have been used with mixed success on highway structures for many years. These materials include silane- or siloxane-based thin film sealers that provide a relatively short-term solution to chloride...
and moisture penetration and must be renewed at least every few years to be effective. Also, many bridge owners have used thicker film barrier coatings of various chemistries, but these have generally carried many trade-offs in terms of application properties and performance.

During the last decade, significant advances have been made in coating technologies that allow highly durable materials to be engineered for specific application and multifunctional performance properties. Coatings now provide both long-term durability in terms of chloride and moisture resistance as well as weatherability and aesthetics. These high-performance products are designed to cure in as little as a few seconds, making rapid application and handling a real possibility.

Examples of modern coating materials specifically engineered to protect concrete structures include breathable waterborne epoxies that can be applied to green concrete, providing a protective film with excellent weathering properties while avoiding the traditional initial waiting period for the concrete to fully dry prior to coating application. Additionally, materials such as aliphatic polyureas and polyurethanes can be designed with zero volatile organic compounds (VOCs), and can be applied from 30 to 250 mils thickness. These materials have excellent ultraviolet (UV) stability, as great as 500% elongation, and can bridge movable cracks up to 1/8 in (3 mm). Cure times for these materials can be engineered to dry to touch from 30 s to <5 min, and have traffic exposure in 2 h, with full cure in 24 h.

A Coordinated Solution
Recognizing the need for a cooperative effort to demystify this rapidly changing technology area, the American Association of State Highway and Transportation Officials (AASHTO) has developed a service intended to provide an unbiased data clearinghouse useful to state bridge owners in prequalifying concrete coatings. AASHTO’s National Transportation Product Evaluation Program’s (NTPEP) efforts in qualifying coatings for steel bridges is well known—some 35 states make use of its data. But until now, no similar program existed for concrete bridge coatings, and every state handles the issue differently (if at all), typically using considerations that are largely aesthetic, not protective.

In 2009, NTPEP approached the coatings industry in an effort to compile information that would identify the appropriate test methods for assessing products in the context of atmospheric exposure and accelerated weathering. With the assistance of industry experts, representatives of the AASHTO member departments developed a consensus-based work plan for performance evaluation of concrete coatings. The resulting work plan—on track to be provided to state transportation departments within the next 12 to 18 months—will help planners develop their qualified product lists to address the various exposure conditions their bridge inventory faces.

This test protocol includes coating evaluations for chloride penetration resistance, weatherability, adhesion to concrete substrates, ability to bridge small surface cracks, and coating material fingerprinting tests.

Multipurpose Coatings as Targeted Investments
Coatings have often been viewed by bridge engineers as an installed maintenance burden—a protective layer that must be maintained frequently or replaced well prior to the end of the useful lifetime of the structure. With modern engineered coatings, this negative connotation can be reversed to focus on the benefit of coatings that provide not only extended durability to concrete structures, but also aesthetics and other functionality. Additionally, the use of exterior coatings on critical concrete structures in concert with advanced high-performance concrete provides a critical risk mitigation for prestressed elements that is affordable, inspectable, and repairable. The key to achieving these significant durability gains will be the development and active sharing of test- and experience-based data on applicability and performance of the many material choices that exist today. AASHTO has taken the lead in this effort and the payoff should begin to be realized in the coming years with the extended cooperation and initiative of bridge owners throughout the country.

Conclusions
Many advancements have been made over recent years in bridge coating technology. Key engineering parameters in the developing technology are advances in design durability, protection for prestressed and post-tensioned construction, and the concept of risk management investment in cost-effective systems that provide increased confidence in bridge construction.

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