A3C15: Committee on Corrosion
Chairman: D. G. Manning

Corrosion Prevention

J. P. Broomfield, *Corrosion Consultant*
D. G. Manning, *Ontario Ministry of Transportation*

Speculating about where the future of the field of corrosion prevention, detection, and rehabilitation might lead is interesting—but not without risk. We all are aware of the revolution in electronics, particularly digital electronics, and information science during the past 20 years. We also should recognize that materials science and technology have undergone a major revolution, bringing us new materials such as plastics, ceramics, and chemicals. The construction industry also has made major advances in automation, equipment, and process control. All of these disciplines will affect the highway construction and maintenance industry during the next few decades. It is against this backdrop that we consider the future of corrosion prevention.

Corrosion is the reaction between a material and its environment. Perhaps the best known example of corrosion is steel; as soon as iron ore has been smelted and refined to produce steel, nature begins to reverse the process. The steel reacts with the environment to form products such as oxides, sulfates, sulfides, and chlorides that no longer have the required physical and chemical properties.

All materials react to some degree in some environments, and one of the responsibilities of the corrosion engineer is to identify materials that will provide the desired life in a given service environment at a reasonable cost. Billions of dollars are spent every year in protecting against, investigating, repairing, and replacing damage due to corrosion. Occasionally, corrosion-induced failures are catastrophic; more often, corrosion is a slow process that can be detected before failure occurs. Therefore, the consequences usually are economic rather than life-threatening.

CORROSION IN THE TRANSPORTATION INFRASTRUCTURE

Much of the transportation infrastructure is built from steel and concrete. The steel may be in structural sections, such as girders, piles, or rails, or embedded in concrete to form reinforced or prestressed concrete. Concrete provides excellent protection to embedded steel because portland cement is highly alkaline, resulting in the formation of a passive layer on the steel surface that protects the steel from further corrosion. However, concrete is also permeable, and even good-quality concrete can be penetrated by aggressive chemical ions. These ions can depassivate the steel, then corrosion begins; because the corrosion products occupy a greater volume than the original metal, the concrete becomes damaged.

Chloride ion, especially as a constituent of sodium chloride, or common salt, is the most common aggressive ion and is of particular concern to the transportation industry. Its presence in seawater affects the performance of coastal structures, and it is the most commonly used chemical for deicing highways and bridges in cold climates. Estimated costs of corrosion damage to bridges vary; however, because many states spend $20 million to $50 million annually, a total figure of $1 billion per year is not unreasonable.

Corrosion of steel in concrete also can be initiated through carbonation of the concrete, which is the reaction with carbon dioxide in the atmosphere. Carbonation can lower the pH of concrete so that it no longer protects embedded steel. The process is much slower than the permeation of chloride ions, and only a few examples of carbonation-induced corrosion have been found in transportation structures in North America. However, as levels of carbon dioxide increase and the infrastructure ages, corrosion resulting from concrete carbonation may become more widespread and of greater concern in the future.

NEW REINFORCED CONCRETE STRUCTURES

Despite the vulnerability of reinforced concrete to corrosion damage, it is unlikely that a significant volume of concrete will be replaced with other materials. Concrete is an inexpensive, effective structural material, and the materials from which it is made are available in most locations. The quality of the concrete used by the transportation industry has been improved and will continue to be improved. Many of the improvements have come from the implementation of new additives; increased use of supplementary cementing materials to replace portland cement; and better placing, consolidation, and curing techniques. As reserves of the highest quality aggregates are depleted and the pressure to use waste and recycled materials increases, a new array of additives may be essential to enable the production of high-quality concrete from marginal aggregates. The far greater number and range of concrete constituents than those used in the past present a potential problem, because the interactions between all possible combinations of materials are not fully understood. Furthermore, the rate at which concrete develops its fundamental properties (such as strength) has changed, so we may no longer be able to rely on the experience that has accumulated over the past decades.

The ability to fabricate components in situ is one of concrete’s biggest advantages (because of its versatility) but also a drawback (because of the variability of constituents, workmanship, and weather). The constraints of site practice limit the improvements that are possible through automation. The use of prefabricated concrete components probably will increase to take advantage of the controlled processes that are available in a factory environment.

Epoxy coatings have been used extensively to protect reinforcing steel against corrosion in new construction. However, recent findings that showed the long-term ineffectiveness of the current coating technology have encouraged the search for improvements and alternatives. Stainless steel and black steel protected by high-performance concrete are increasingly being used while the search for effective and economical alternatives continues. Alternative ways of reducing the cost of stainless steel, such as through the use of alloys or as cladding for mild steel bars, are anticipated. Nonmetallic reinforcements such as glass, polypropylene, and aramid fibers are being investigated as replacements for reinforcing and prestressing steel. The grout that protects the high-strength steel in post-tensioned concrete construction always has been the weak link in the defense against corrosion. New materials and methods have been developed, and more demanding specifications have been written.

On the design side, efforts toward preventing or reducing corrosion will continue. There always will be a balance. The use of less reinforcing steel increases the size and weight of components. Increased cover increases the risk of surface cracks, which can be counterproductive. Increased site supervision to ensure that proper cover is achieved increases construction costs. However, it is likely that less reinforcing steel will be used in critical locations most vulnerable to corrosion; instead, it will be a material highly resistant to corrosion. Better site practices and quality systems will improve durability and extend the service life of the transportation infrastructure.

Often, insufficient attention has been given to designing structures that can be inspected, maintained, and rehabilitated. Examples include cells that are inaccessible, single-load paths that require closure of the structure to rehabilitate critical components, and not providing for convenient parts replacement (e.g., for joints and bearings) or for cleaning (e.g., of gutters and drains). The serviceability of a bridge must be considered more carefully at the design stage, and maintenance manuals must be written in much the same way as for an automobile or a piece of machinery.

REHABILITATING REINFORCED CONCRETE STRUCTURES

Many corrosion-related issues related to the rehabilitation of existing structures are much more complex than those for new construction. For example, the extent of corrosion damage must be investigated, and decisions must be made regarding the amount of concrete to be removed and the repair method. In addition, the work must often be carried out while the structure remains open to traffic. Working conditions are often difficult and might limit consideration of the repair methods to those that can be completed quickly, even though other techniques may be more effective.

Milling and hydrodemolition often are used to remove the surface layer of concrete, especially from bridge decks, whereas percussion tools are used to remove concrete from around the reinforcing bars. The work is tedious, labor-intensive, costly, and often hazardous. New methods of concrete removal that are safe, effective, economical, and environmentally acceptable are required. Ideal methods would allow workers to control the depth of removal, would not damage the concrete or reinforcing steel left in place, and would remove concrete from around the reinforcing steel. Ideally, the methods also would clean the reinforcing steel to avoid the expense and environmental consequences of abrasive blasting. Much of the development work that has been completed to date has concentrated on removing concrete from reinforced concrete structures. Additional work is required to examine the complexities of removing concrete from prestressed concrete structures.

Equally important as the methods used for removing concrete when rehabilitating a corrosion-damaged structure are the criteria used for concrete removal. The more chloride-contaminated concrete left in place and the greater the amount of corrosion products left adhering to the reinforcement, the greater the risk of additional corrosion damage after repair—unless steps are taken to prevent additional corrosion, for example, by applying cathodic protection. The area of predicting service life is an emerging technology that has potentially large benefits. Studies are needed to relate the effect of concrete removal to the service life of rehabilitated structures and thereby to identify the concrete removal criteria associated with the most cost-effective method of rehabilitation. As we improve our ability to model the corrosion process and predict durability, we should be able to calculate the optimum investment in initial cost, maintenance, and rehabilitation for the design life of any structure.

Detecting corrosion and corrosion-induced deterioration in reinforced concrete is difficult, but asphalt-covered bridge decks and prestressed concrete components are especially difficult to investigate. The ability to detect deterioration is limited by the physics involved. To detect a change in an interrogating waveform, the length of the wave must be about the same size as the defect. Thus, for stress waves, the waves must be in the hypersonic range (>10^{10} Hz); however, these waves are subject to the greatest attenuation and therefore penetrate concrete poorly. For electromagnetic waves, the shortest waves are X rays and gamma rays; however, these waves also have the greatest energy, and the use of X rays and gamma rays poses serious practical and economic difficulties in the field. Substantial developments in digital processing and artificial intelligence during recent years probably will bring improvements in detecting deterioration through the application of improved signal processing and pattern recognition rather than entirely new methods. Measuring the rate of corrosion is relatively new; consequently, we anticipate the emergence of new methods that provide more accurate and extensive data. Rapid evaluation of bridge decks using vehicle-mounted devices such as radar is becoming more routine, and the method continues to be developed.

Our ability to survey and monitor entire structures, rather than individual components, will continue to improve. With the availability of modern digital processing and communications systems, permanent corrosion monitoring is increasingly feasible and economical, especially on prestige transportation structures. This technology, which is built into the structure to monitor and report on the condition of the structure, falls under the umbrella of "smart structures."

In the field of cathodic protection, anodes are being developed all the time with new coatings and other new materials. Development may take one of two different directions: Systems will become either simpler and require lower maintenance (i.e., less checking and adjustment) or more sophisticated and encompass remote monitoring, remote control, and alarms that advise the owner of malfunctions and maintenance needs. Research on sacrificial anode cathodic protection is under way to determine whether these simple, low-maintenance systems can be used effectively on bridge decks, substructures, and elsewhere. Electrochemical chloride extraction is moving steadily from the trial-and-experimental application stage to full-scale applications.

The use of corrosion inhibitors for steel in concrete is still in its infancy. Inhibitors have been used in new construction, and research studies have been conducted to identify materials and processes that can be used effectively to reduce corrosion in existing salt-contaminated structures. This technology presents considerable opportunity, because a corrosion inhibitor that could be applied to a concrete surface would avoid the significant expense of removing concrete that is physically sound, yet contaminated with chloride ions.

STEEL STRUCTURES

Structural steel components are protected against corrosion by applying a protective coating to the steel or by using a steel that is resistant to atmospheric corrosion. Such steel, often called "weathering steel," develops a stable oxide layer that is resistant to further corrosion. It performs well except in situations where the components remain wet, especially when salt (from the ocean or deicing applications) is present. The most important requirements are to identify exposure conditions under which weathering steel will perform satisfactorily and to avoid structural details that will trap and retain moisture and salt. As with many cases of corrosion-related distress, the corrosion engineer is concerned more with details and microclimate effects than with macroclimate effects, which usually are understood.

In the field of structural steel coatings, environmental pressure for a low-volatile-organic component has encouraged the use of water-based coatings. The biggest challenge in the coating industry is to find ways to recoat bridges without removing existing lead-based paint and thus avoiding the expense of negative-pressure enclosures and disposal of the spent blasting material. These requirements have led to the development of overcoating technology, in which only loose paint is removed; methods of removing paint by mechanical and chemical methods rather than abrasive blasting; and the development of coatings that tolerate low-quality surface preparation. Working conditions on coating contracts often are hazardous, and the industry is ripe for the introduction of robots for both surface preparation and coating applications.

ALTERNATIVE DEICERS

Surprisingly, although the costs of corrosion are massive, they still do not tilt the financial balance in favor of any of the alternative deicers or salt-containing corrosion inhibitors except in a few very specialized applications. Salt occurs widely in nature, is a very effective deicer, is inexpensive, and has a known environmental impact. All synthetic alternatives are less effective, more expensive, and generally must be applied to a lot of highway to protect a few bridges. The road to a cost-effective alternative to deicing salt is going to be a long one.

Although self-evident, it is worth noting that a switch to a noncorrosive deicer would have little or no impact on the corrosion of coastal structures. In other words, dealing with corrosion problems in some components of the transportation infrastructure always will be a challenge.

IMPEDIMENTS TO CHANGE

One problem facing innovators is the time needed to see a return on investment in developing a new product or process. The construction industry is notoriously cautious and seemingly slow to accept new technology, and the transportation industry is so fragmented that individual owners insist on conducting lengthy trials. Furthermore, the public sector is often legally prohibited from specifying acquisitions from a sole source. These problems have been recognized, and attempts have been made to create a marketplace that is more receptive to innovation. However, additional progress is needed in structuring contracts so that risk and innovation are rewarded adequately.

FUTURE CHALLENGES

We always will need to build transportation structures in corrosive environments. Therefore, we will need innovative materials, better methods of investigation, and improved repair techniques to deal with problems not yet identified. For example, how will we repair problems that develop in the fiber-optic cables used in freeway management systems, now being embedded in miles of concrete median barrier? Climate changes due to global warming and the greenhouse effect also will produce more corrosive conditions. Higher temperatures accelerate corrosion, and greater concentrations of carbon dioxide will increase carbonation rates and the acidity of rainfall. The construction and repair industry will continue to need engineers and corrosion specialists with knowledge of and experience in dealing with corrosion problems. Specialists with sound academic training and solid field experience are the most important resource in the fight against corrosion, which will continue into the new millennium.