Cathodic Protection as a Corrosion Control Alternative

By William T. Scannell and Ali Sohanghpurwala

Corrosion of reinforcing steel in concrete is a widespread and enormously costly problem in all parts of the United States. Numerous concrete structures including bridge decks and substructures, parking garages, balconies and others are deteriorating as a result of reinforcing steel corrosion. Virtually any reinforced concrete structure is susceptible to the ravages of corrosion if subjected to the right environment.

The corrosion process that takes place in concrete is electrochemical in nature, very similar to a battery. Electrochemical corrosion is corrosion which is accompanied by a flow of electrons between cathodic and anodic areas on a metal surface. In concrete the electro-chemical corrosion reactions are most often triggered when three factors—chloride, oxygen and moisture—meet at the reinforcing steel surface. A sort of natural battery develops within the reinforced concrete structure, generating a low-level internal electrical current. The points where this current leaves the metal surface and enters the concrete electrolyte are called anodes. The current leaving the concrete and returning to the steel does so at the cathodes. Corrosion or oxidation (rust) occurs only at anodes.

When corrosion of reinforcing steel occurs, the rust products occupy more volume than the original steel, causing tension forces in the concrete. Since concrete is relatively weak in tension, cracks soon develop as shown in Figure 1, exposing the steel to even more chlorides, oxygen and moisture—and the corrosion process accelerates. As corrosion continues, delaminations—separations within the concrete and parallel to the surface of the concrete occur. Delaminations are usually located at, or near, the level of reinforcing steel. Eventually concrete chunks break away or spall off.

Visual signs of corrosion-induced damage on many types of reinforced concrete structures are becoming more and more prevalent. In many parts of the country one can hardly drive across a bridge or enter a parking garage that doesn't have some degree of corrosion damage.

The rate of concrete deterioration at any given time is dependent on many factors including corrosion rate, reinforcing steel concentration, concrete properties, cover and the environment, to name a few. Once corrosion has begun there is one thing for certain—it will only get worse and it will do so at an ever-increasing rate. Ultimately, if corrosion is allowed to continue, structural integrity can be compromised due to loss of section of the reinforcing steel and/or loss of bond between the steel and the concrete, and replacement may be the only solution.

In order to mitigate or control a corrosion problem (provide low future maintenance and long term protection) specific information is needed for any given structure. Fortunately, proven technology and scientific methods are available to evaluate corrosion of reinforcing steel (and other embedded metals) and associated damage on reinforced concrete structures. These techniques are designed to determine the extent of damage, define the corrosion state of steel in undamaged areas, evaluate the cause, or causes, of corrosion, and determine the potential for the steel to corrode in the future resulting in further damage. It is only after this information is obtained through a detailed corrosion condition evaluation that a suitable repair and protection specification can be developed for a corrosion-plagued structure. It is important to point out that concrete itself can deteriorate regardless of the condition of embedded reinforcement. Examples of this include freeze/thaw damage and alkali-silica reactions. Various concrete tests are therefore often conducted as part of an overall evaluation.

Although there are similarities between corrosion of conventionally reinforced concrete structures and pre-tensioned or post-tensioned structures, the majority of this article applys to conventionally reinforced concrete structures only, particularly with

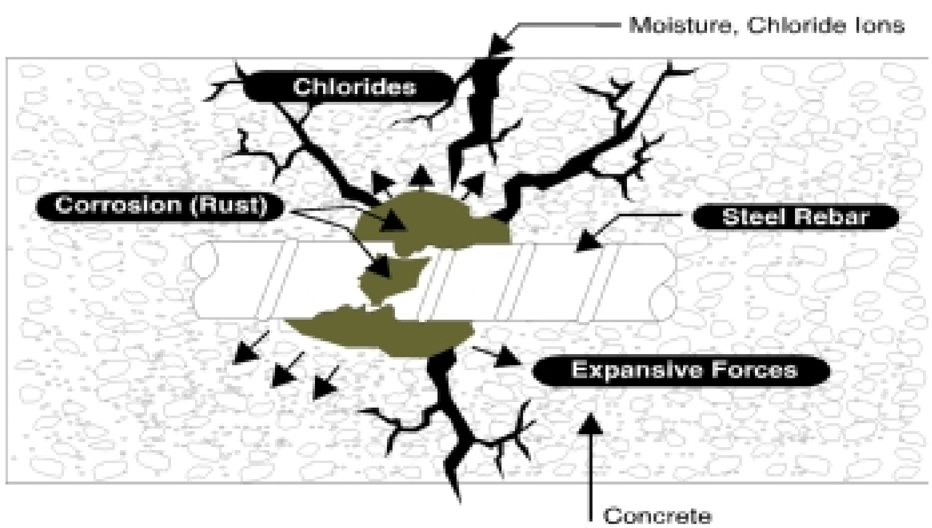

Figure 1. Schematic of concrete deterioration due to corrosion. (Diagram: Report No. FHWA-DP-34-3 12/88)

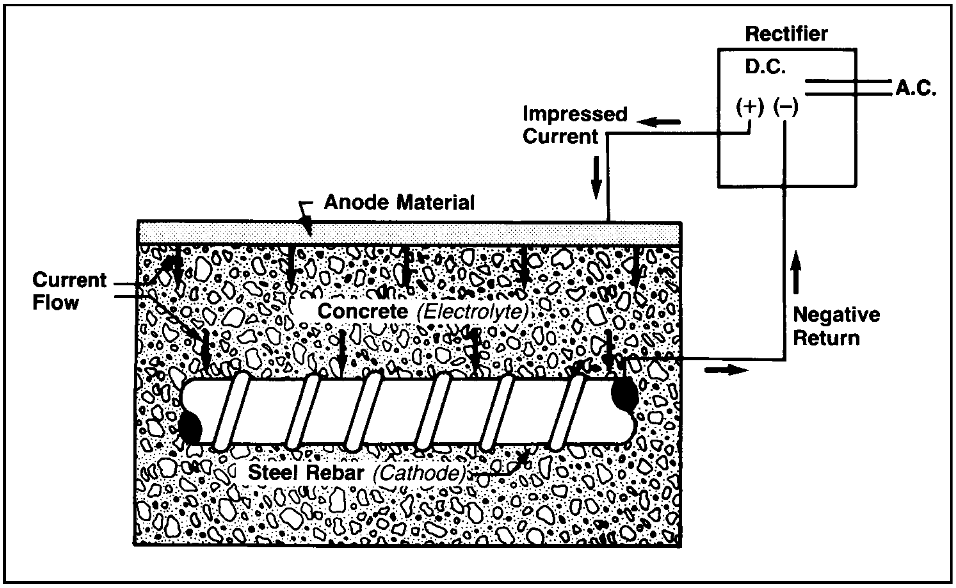

Figure 2. Basic layout required for cathodic protection. (Diagram: Report No. FHWA-DP-34-3 12/88)

respect to the applicability of cathodic protection.

Cathodic Protection

What is cathodic protection? Simply put, cathodic protection (CP) is a widely used and effective method of corrosion control. Many people, engineers included, think cathodic protection is some kind of voodoo. Others believe CP is so complicated and expensive that it has no practical use in the concrete rehabilitation industry. Then there are those who say CP doesn't work or that it is unreliable in the long term. The facts, however, show that CP is not so complicated, is often the most cost-effective course of action, has practical application on reinforced concrete structures, and that it most definitely works. Of course, performance of CP systems, like all other corrosion protection systems, is directly dependent on sound specifications, proper installation, and monitoring and maintenance. With CP, one cannot simply install it and forget it. Good long term performance of all CP systems requires good monitoring and maintenance procedures, a reason why CP is sometimes discounted as an alternative protection system. What some investigators and specifiers apparently don't recognize is that there is no such thing as a corrosion protection system which does not require periodic inspection and maintenance. In fact, some corrosion protection systems actually require periodic replacement or reapplication.

For decades, cathodic protection has been successfully used to protect pipelines, ship hulls, off shore oil platforms, heat exchangers, underground tanks, and many other facilities exposed to a corrosive environment. Granted, its first application to steel in concrete was only in 1973, but we've come a long way since then. Cathodic protection of steel in concrete is simply a means of fighting fire with fire, or in this case, electricity with electricity. The corrosion process generates electric currents. Cathodic protection supplies a source of external current to counteract the corrosion current. Hence, corrosion stops, or at least is greatly minimized.

After millions of dollars of research in the areas of corrosion of steel in concrete and corrosion mitigation, cathodic protection evolved as the only technique which could positively arrest corrosion of steel in existing concrete structures. In fact, some time ago the Federal Highway Administration (FHWA) acknowledged that cathodic protection was the only rehabilitation technique that had proven to stop corrosion in salt-contaminated bridge decks regardless of the chloride content in the concrete. It should be noted, however, that CP is not always needed nor is it applicable on every structure. More on this later.

Types of CP Systems

Cathodic protection systems can be grouped into two basic types; impressed current systems and galvanic, or sacrificial anode, systems. In both types of systems, the reinforcing steel is forced to function as a cathode, hence the name cathodic protection. Anodes and cathodes exist on a corroding rebar and corrosion occurs at the anode, but with CP an auxiliary anode is used to force the entire rebar to function as a cathode.

Impressed current cathodic protection is achieved by driving a low voltage direct current from a relatively inert anode material, through the concrete to the reinforcing steel. Figure 2 shows the basic layout required for impressed current cathodic protection systems. Direct current of sufficient magnitude and direction is applied, so as to oppose the natural flow of current resulting from the electrochemical corrosion process. The direct current is supplied by an external power source, most often a CP rectifier. Recently, the use of solar power has received attention and research is underway.

Galvanic, or sacrificial anode, cathodic protection, is based on the principles of dissimilar metal corrosion and the relative position of specific metals in the Galvanic series. No external power source is needed with this type of system and much less maintenance is required. Such systems also provide protective current primarily to areas on the steel surface which need it the most. However, the relatively high resistivity of concrete led to early opinions that the low driving voltage provided by such systems would be inadequate for cathodic protection

Figure 3. Workmen install Coke asphalt CP system.

Figure 4. Mounded conductive polymer CP system.

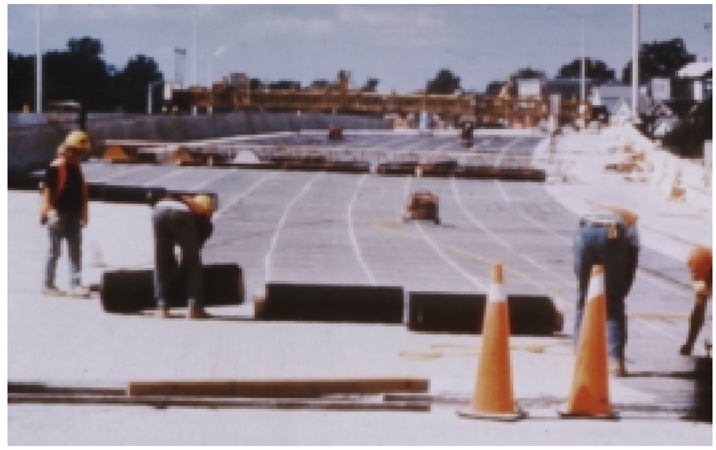

Figure 5. Titanium based anode mesh system.

of steel in concrete. Actual research and testing of galvanic CP systems has thus been limited, except in Florida. The Florida Department of Transportation has conducted extensive research and has reported much success in the use of galvanic anode CP systems on bridge substructure members in marine environments. This can probably be attributed to the lower resistance moist concrete found in marine substructures and innovative CP designs.

The zinc on galvanized reinforcing steel functions as a sacrificial anode much the same way as zinc in a sacrificial anode CP system does. In this case, the steel is protected by the zinc from the day the rebar is galvanized. However, once all the zinc is consumed, the base steel will be susceptible to corrosion in the same way as plain reinforcing steel.

Another example of a sacrificial anode in concrete is aluminum (for example, balcony railings) in contact with reinforcing steel. This situation is similar to galvanized reinforcing steel, although it is not a favorable or intentional application of sacrificial anode protection. It is well known that corrosion of embedded aluminum in concrete can occur and crack the concrete. The situation can be made worse, however, if the aluminum is in contact with reinforcing steel. Aluminum, being more active than steel, can act as a sacrificial anode to protect the reinforcing. Hence, misapplication or accidental application of sacrificial anodes can have undesirable consequences.

As stated earlier, cathodic protection has evolved as the only proven procedure for effectively mitigating and controlling corrosion of steel in existing chloride-contaminated conventionally reinforced concrete structures. The characteristics, relevant design parameters, development of necessary components, limitations, installation procedures and performance history of many types of CP systems for concrete structures containing mild reinforcing steel have been extensively researched and documented. The widespread use of cathodic protection and the need for design, installation, testing, performance and maintenance guidelines, prompted the National Association of Corrosion Engineers (NACE) to compile and issue a standard recommended practice for "Cathodic Protection of Reinforcing Steel (conventional mild steel) in Atmospherically Exposed Concrete Structures." In addition, standard specifications for cathodic protection of reinforced concrete bridge decks will soon be available from the American Association of State Highway and Transportation Officials (AASHTO).

Selection of CP for Corrosion Control on Reinforced Concrete Structures

As discussed earlier, CP is not always needed nor is it necessarily applicable on every structure. The first step is to have a concrete and corrosion condition survey conducted in order to define the cause and extent of the problem. With the results of a thorough condition survey at hand, the engineer must analyze the data and make a determination on the type of repair and protection method to use. If cathodic protection is chosen then another determination must be made in order to choose the most appropriate system for the conditions encountered.

To select and design a proper repair and protection scheme it is imperative that the cause, or causes, of the distress are properly diagnosed and fully understood, and that the extent of damage is determined. Before selecting cathodic protection for a given structure a number of issues need to be considered. Some of these include:

Is the owner looking for long term rehabilitation (say greater than 15 or 20 years)? Cathodic protection is usually most cost effective when long term rehabilitation is desired. The amount of damaged concrete is another factor in choosing CP. If only a small amount of delamination and spalling has occurred, CP may not be the most appropriate choice for future protection. Similarly, if the majority of a concrete structure is badly deteriorated, replacement may be in order. The in-between situations require consideration of other information gathered from the condition survey. One advantage of CP is that removal of sound concrete is not required, thus a considerable cost savings may be realized. It may be a viable alternative to removing two or three inches of concrete over a large area in order to prevent future corrosion.

The corrosion rate of the reinforcing steel must also be considered. If the corrosion rate is high in areas which are yet undamaged, conventional repairs will not aid in controlling future corrosion. Actually stopping or slowing the rate to an acceptable level may be necessary, and CP is the only technique which is presently available for accomplishing this.

Electrical continuity of the reinforcing steel to be protected is also a primary factor in considering CP. A closed electrical circuit (unbroken electrical path) between all reinforcing steel is required in order for the CP system to function properly. Electrical continuity testing can be done during the

Figure 6. Both the mounded conductive polymer and titanium mesh anode systems require a cementitious overlay as shown.

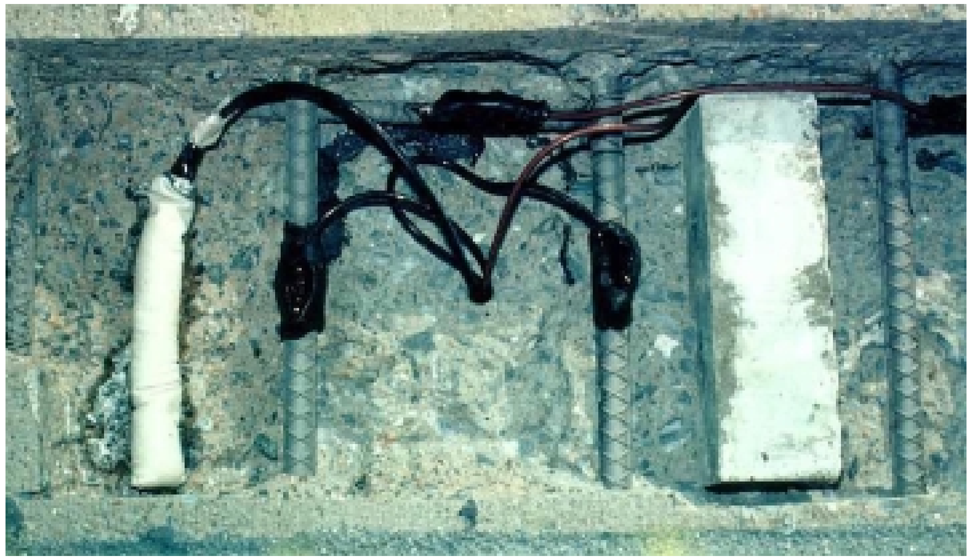

Figure 7. Typical instrumentation.

condition survey.

The chloride concentration in the concrete throughout the structure is also important. If sufficient chlorides are present at the reinforcing steel depth in many areas of the structure, CP may be the economically viable alternative. However, if the chloride content is relatively low, or if the chlorides are generally located only in isolated areas of the structure, another corrosion protection system may be most appropriate.

Another factor to consider is whether or not the concrete distress was solely caused by corrosion of reinforcing. For example, if freeze/thaw or alkali-silica reaction problems are encountered, CP is not the way to go. Such deterioration will continue with or without cathodic protection. In fact, in the case of alkali-silica reactions, recent research indicates that CP current can actually accelerate the reactions.

Figure 8. Perforated zinc cage which is the sacrificial anode used in some CP systems.

There are many things to consider in selecting a suitable rehabilitation plan for a deteriorated concrete structure. A few of the most important issues related to CP have been mentioned here. In many cases, a life cycle cost analysis is useful in selecting the most appropriate rehabilitation method.

As discussed earlier, once CP has been selected, the exact type of CP system must be chosen. The type of anode is one of the most critical components of a CP system. The particular application may preclude the use of some of the available anodes and CP systems. The type of surface to be protected (top surface, soffit, vertical, etc.) and its geometry, concrete cover over reinforcing steel, the environment in and around the structure, and structural considerations, such as whether the structure can support the additional dead load resulting from some CP systems, are all important factors in selecting a specific CP system.

There are several different types of impressed current and sacrificial anode CP systems. For the purposes of this article, some typical CP systems used on bridge decks and substructures are shown. Some of these systems are also widely used on other types of structures and other systems, not shown here, are also being utilized.

Figures 3 through 6 show some of the typical CP systems used on bridge decks. Briefly, Figure 3 shows a coke asphalt CP system, Figure 4 shows a mounded conductive polymer CP system and Figure 5 presents a titanium based anode mesh system. Both the mounded conductive polymer and titanium mesh anode systems require a cementitious overlay as shown in Figure 6. All CP systems require some amount of embedded instrumentation for monitoring purposes. Some typical instrumentation is shown in Figure 7.

Some of the CP systems used on bridge substructures are shown in Figures 8 through 11. Figure 8 shows a perforated zinc cage which is the sacrificial anode used in some CP systems on concrete bridge pilings. Figures 9 and 10 show the integral pile jacket CP system (used on bridge pilings) which incorporates a titanium based anode. This is an impressed current type of CP system. Figure 11 shows a flame sprayed zinc CP system which provides sacrificial CP. Flame sprayed zinc is also used in impressed current cathodic protection.

Summary

Reinforcing steel corrosion has caused an enormous amount of damage on many different types of concrete structures, and is an ongoing problem throughout the United States. Fortunately, proven methods are available to evaluate corrosion of reinforcing steel and the associated damage on reinforced concrete structures. These tools allow one to determine the extent of damage, define the corrosion state of steel in undamaged areas, evaluate the cause, or causes, of corrosion, and determine the potential for the steel to corrode in the future resulting in further damage. Other methods are also available to investigate concrete deterioration processes unrelated to reinforcing steel corrosion. It is only after the required information is obtained through a detailed concrete and corrosion condition evaluation that a suitable repair and protection specification can be developed for a deteriorated reinforced concrete structure.

Figure 9 (above) and Figure 10 (right). Integral pile jacket CP system.

Cathodic protection is a widely used and effective method of corrosion control for reinforced concrete structures. Cathodic protection supplies a source of external current to counteract the corrosion current. Hence, corrosion stops, or at least, is greatly minimized.

Almost any atmospherically exposed reinforced concrete structure or portion of reinforced concrete structure of almost any geometry can be cathodically protected. However, existing structures must be considered individually with regard to the need for and applicability of CP. Remember, not all structures are good candidates for CP, but CP is the only system that can truly retard or mitigate corrosion. Before selecting cathodic protection for a given structure a number of issues need to be considered. If CP is chosen then several other points must be taken into account in order to choose the most appropriate system for the conditions encountered.

In the author's opinion, those involved in recommending or specifying concrete repair and protection systems owe it to their clients to become familiar with CP and to consider its application when appropriate.

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Figure 11. Flame sprayed zinc CP system which provides sacrifical CP

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