

Understanding Corrosion and Cathodic Protection of Reinforced Concrete Structures

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Corrosion of Steel in Concrete

The corrosion process that takes place in concrete is electrochemical in nature, very similar to a battery. Corrosion will result in the flow of electrons between anodic and cathodic sites on the rebar. For corrosion to occur four basic elements are required:

- Anode – site where corrosion occurs and current flows from.
- Cathode – site where no corrosion occurs and current flows to.
- Electrolyte – a medium capable of conducting electric current by ionic current flow (i.e. soil, water or concrete).
- Metallic Path – connection between the anode and cathode, which allows current return and completes the circuit.

Reinforcing steel in concrete normally does not corrode because of the formation of a passive oxide film on the surface of the steel due to the initial corrosion reaction. The process of hydration of cement in freshly placed concrete develops a high alkalinity, which in the presence of oxygen stabilizes the film on the surface of embedded steel, ensuring continued protection while the alkalinity is retained. Normally, concrete exhibits a pH above 12 because of the presence of calcium hydroxide, potassium hydroxide, and sodium hydroxide - the term pH is a measure of the alkalinity or acidity, ranging from highly alkaline at 14 to highly acidic at zero, with neutrality at 7. Although the precise nature of this passive film is unknown, it isolates the steel from the environment and slows further corrosion as long as the film is intact. However, there are two major situations in which corrosion of reinforcing steel can occur. These include:

1. Carbonation, and
2. Chloride contamination

Carbonation is a process in which carbon dioxide from the atmosphere diffuses through the porous concrete and neutralizes the alkalinity of concrete. The carbonation process will reduce the pH to approximately 8 or 9 in which the oxide film is no longer stable. With adequate supply of oxygen and moisture, corrosion will start. The penetration of concrete structures by carbonation is a slow process, the rate of which is determined by the rate at which carbon dioxide can penetrate into the concrete. The rate of penetration primarily depends on the porosity and permeability of the concrete. It is rarely a problem on structures that are built with good quality concrete with adequate depth of cover over the reinforcing steel.

The roll of the chloride ion in inducing reinforcement corrosion is well documented. Chloride ions can enter into the concrete from de-icing salts that are applied to the concrete surface or from seawater in marine environments. Other sources include chloride containing admixtures which are used to accelerate curing, contaminated aggregates and/or mixing water, air born salts, salts in ground water, and salts in chemicals that are applied to the concrete surface. If chlorides are present in sufficient quantity, they disrupt the passive film and subject the reinforcing steel to corrosion.

The levels of chloride required to initiate corrosion are extremely low. There have been many recommendations, both codes and publications, for maximum chloride concentrations. The American Concrete Institute (ACI) Publication 222R-96 "Corrosion of Metals in Concrete", recommends the following chloride limits in concrete for new construction, expressed as a percent by weight of cement (acid-soluble test method):

- Pre-stressed concrete 0.08 %
- Reinforced concrete in wet conditions 0.10 %

- Reinforced concrete in dry conditions 0.20 %

Field experience and research have shown that on existing structures subjected to chloride ions, a threshold concentration of about 0.026% (by weight of concrete) is sufficient to break down the passive film and subject the reinforcing steel to corrosion. This equates to 260-ppm chloride or approximately 1.0 lb/yd³ of concrete.

The removal of the passive film from reinforcing steel leads to the galvanic corrosion process. Chloride ions within the concrete are usually not distributed uniformly. The steel areas exposed to higher concentrations of chlorides start to corrode, and breakdown of the oxide film eventually occurs. In other areas, the steel remains passive. A classic example of this uneven exposure is the application of de-icing salts to a bridge deck in which the top mat of steel receives more chloride than the bottom mat. This uneven distribution results in macro-cell corrosion, in which large anodic sites on the top mat and large cathodic sites on the bottom mat are encountered. The concrete acts as the electrolyte and the metallic conductor is provided by wire ties, chair supports, and the steel bars. **Figure 1** illustrates how a macro corrosion cell can develop from differences in chloride ion concentration.

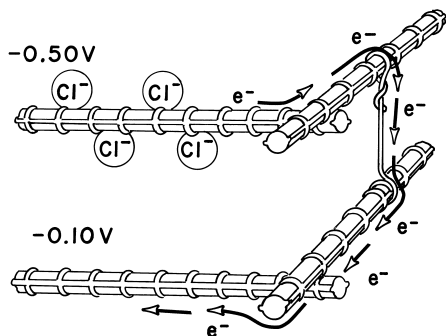


Figure 1. Differences in chloride ion concentration establish differences in electrical potential.

Patching of delaminated and spalled concrete with conventional concrete is yet another example of the corrosion mechanism. Strong electrochemical macro-cells are established near the interface between the old chloride-contaminated concrete and the new chloride-free

concrete. The short distance between anode and cathode, together with the large difference in chloride concentration, result in strong potential gradients, which accelerate corrosion. Such a macro-cell is shown in **Figure 2**. In many cases, this kind of repair will require rehabilitation again in only one or two years.

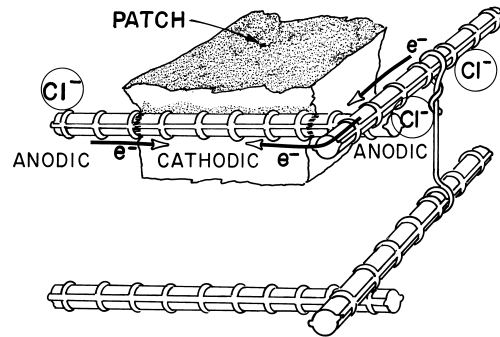


Figure 2. Macro-cell corrosion through concrete patching.

Differences within the grain structure of the metal or different residual stress levels can also lead to galvanic corrosion. When chlorides are uniformly distributed around the steel, local action micro-cells form and dominate the corrosion process. Anodic and cathodic sites may be observed very close to each other on the same bar under such circumstances. This micro-cell effect generally leads to a type of localized corrosion known as pitting corrosion. In this case, metal loss from anodic sites creates a pit. As corrosion proceeds, the condition inside the pit becomes progressively more acidic and further loss occurs from the bottom of the pit rather than from the sides. The cross-sectional area of the steel is progressively reduced to a point in which the steel can no longer carry the applied loading.

All of the corrosion processes described above require oxygen. In the absence of oxygen, the corrosion rate is appreciably reduced even with chloride concentrations above the threshold level, except in acid solutions. However, keeping oxygen from reinforcing steel in the field is extremely difficult, if not impossible. When corrosion of reinforcing steel occurs, the corrosion products or rust can occupy several times the volume than the original steel, causing tensile forces to develop in the concrete. Since concrete is relatively weak in tension, cracks can

develop as shown in **Figure 3a**, 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 concrete surface occur (**Figure 3b**). Delaminations are usually located at, or near, the level of the reinforcing steel. Eventually pieces of concrete break away forming spalls in the concrete (**Figure 3c**), which require repair to maintain structural integrity.

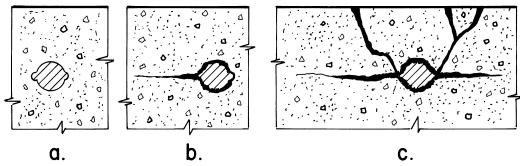


Figure 3. Corrosion-induced cracking of the concrete.

Cathodic Protection Fundamentals

There are many ways to slow down the corrosion process, however cathodic protection (CP) is the only technology that has proven to stop corrosion in existing reinforced concrete structures, regardless of the chloride content in the concrete.

What is CP? Quite simply CP is a widely used and effective method of corrosion control. In theory it is defined as the reduction or elimination of corrosion by making the metal a cathode via an impressed direct current (DC), or by connecting it to a sacrificial or galvanic anode. Cathodic areas in an electrochemical cell do not corrode. By definition, if all the anode sites were forced to function as current-receiving cathodes, then the entire metallic structure would be a cathode and corrosion would be eliminated.

For decades, CP has been successfully used to protect underground pipelines, ship hulls, offshore oil platforms, underground storage tanks, and many other structures exposed to corrosive environments. The first application of CP to a concrete structure was a bridge deck in 1973. This system continues to function with no physical delamination of the concrete. CP of steel in concrete is quite simply a means of fighting fire with fire, or in this case, electricity with electricity. The corrosion process generates electric currents. CP supplies a source of external

current to counteract the corrosion current. Hence, corrosion can be eliminated.

As indicated above, there are two types of CP systems – impressed current and galvanic. An impressed current CP system for concrete structures may require the following basic components:

- DC power supply (rectifier).
- Inert anode material, such as catalyzed titanium anode mesh.
- Wiring and conduit.
- Instrumentation, such as embedded silver/silver-chloride reference electrodes.

A schematic of an impressed current CP system using catalyzed titanium anode mesh is shown in **Figure 4**.

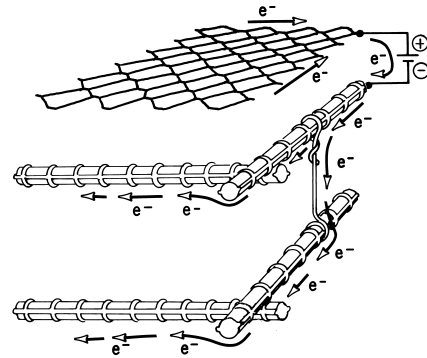


Figure 4. Schematic of impressed current CP system.

A rectifier is used to convert alternating current (AC) to direct current. A rectifier works on the same principle as an AC adapter for a computer or a battery charger. In an impressed current CP system, the rectifier provides the power (i.e. low voltage direct current) and controls the amount of power to each zone. Rectifiers are available in many types and operating outputs. Mainly, they are designed to provide either constant current or constant voltage to the anode system.

The anode is one of the most critical components for a cathodic protection system. It is used to distribute protective current to the reinforcing steel and provides locations for anodic reactions to take place in lieu of the reinforcing steel. By using relatively inert materials, such as catalyzed titanium, anode consumption is minimized. One

of the main benefits of catalyzed titanium is that its life expectancy can be determined through accelerated life testing. N.A.C.E. Standard TM0294-94, "Testing of Embeddable Anodes for Use in Cathodic Protection of Atmospherically Exposed Steel-Reinforced Concrete" gives procedures for accelerated life testing of these anodes. Based on test results using this method, it has been found that the life of catalyzed titanium anodes can readily exceed 40 years for existing structures, and over 100 years for new reinforced concrete structures (i.e. cathodic prevention). **Figure 5** shows the application of ELGARD™ titanium anode mesh to a bridge deck. The mesh is subsequently covered with a concrete overlay.



Figure 5. ELGARD Anode Mesh installation on a bridge deck

A sacrificial or galvanic anode system for reinforced concrete uses a more reactive metal (anode) such as zinc or aluminum-zinc-indium (Al-Zn-In), to create a current flow. Sacrificial anode systems are based on the principle of dissimilar metal corrosion and the relative position of different metals in the galvanic series. The direct current is generated by the potential difference between the anode and reinforcing steel when connected. The sacrificial anode will corrode during the process and is consumed. Current will flow from the anode, through the concrete, to the corroding reinforcing steel. Galvanic anodes may be installed as cast anodes in soil or thermally sprayed onto atmospherically exposed concrete to form a sacrificial coating. **Figure 6** shows the arc-spray application of an Al-Zn-In coating to a reinforced concrete bridge pier.



Figure 6. Arc-spray application of sacrificial Aluminum-Zinc-Indium

Galvanic CP systems have the benefit of no auxiliary power supply and the advantage of being used for pre-stressed or post tensioned concrete without the risk of elevated potential levels, which can lead to hydrogen embrittlement of the steel. The anode life, however, may be relatively short as compared to the inert anodes, which are used with impressed current systems. Also, the current that is produced by a galvanic anode is a function of its environment (i.e. moisture and temperature conditions) and the output cannot be easily adjusted or controlled as with the impressed current method.

Reference electrodes are used to evaluate cathodic protection levels. They may be portable devices or permanently embedded probes in the concrete structure. The most commonly used embedded reference electrodes are silver/silver chloride (Ag/AgCl). Reference electrodes should have a separate ground connection to the reinforcing steel. CP systems also require a negative connection to the reinforcing steel (return path for electric current).

With CP, chloride ions will slowly migrate away from the reinforcing steel and toward the anode. Furthermore, the production of hydroxide ions at the steel surface will cause the concrete to revert back to an alkaline state. These factors when taken together will quickly arrest the corrosion process when current is applied, and allow the passivating film to reform on the surface of the reinforcing steel. It is important to realize that with cathodic protection corroded reinforcing steel cannot be restored to its original native state, but corrosion of steel in concrete can be effectively stopped through the application of cathodic protection.

When evaluating a structure as a candidate for cathodic protection, several parameters should be considered. These may include:

- Remaining service life should be > 10 years.
- Delaminations and spalls should be < 50% of structure area.
- Chloride content should be > 0.026% by weight of concrete (1.0 lbs./yd³).
- Half-cell potentials should be > -200 mV, indicating a breakdown of the passivating film.
- The candidate structure should be structurally sound.
- The majority of reinforcing steel bars should be electrically continuous.
- AC power should be available.

The process of cathodic protection for reinforced concrete structures surprisingly takes little power. Data has shown that typical CP operating current densities range between 0.2 and 2.0 mA/m² for cathodic prevention of new reinforced concrete structures, as compared with 2 to 20

mA/m² for CP of existing salt contaminated structures. This will result in power consumption ranging from 1-3 watts per 1,000 m² of concrete for new construction, and 3-15 watts per 1,000 m² for existing structures.

Once the CP system has been installed it is necessary to provide routine monitoring and maintenance. For impressed current systems, this involves visual inspection of the system and periodic checks at the power supply to ensure proper operation. As a minimum, the periodic checks should entail measurement of the voltage and current for each anode zone. Ensuring the supply of direct current from the rectifier to the structure in accordance with the operation and maintenance manual is the most important operating parameter. Remote monitoring systems may also be incorporated to help facilitate monitoring of the rectifier. As indicated above, galvanic anode systems have no power supply and therefore they require minimal monitoring and maintenance.

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