Treating Reinforcement Corrosion in Parking Structures

by Steven J. Susca, PE

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PARKING GARAGES ARE AN INTEGRAL PART OF OUR NATION'S INFRASTRUCTURE. ALTHOUGH THEY ARE SUBJECT TO MORE DETERIORATION THAN OTHER BUILDING TYPES, THEIR MAINTENANCE IS TYPICALLY NOT CONSIDERED OF PRIMARY IMPORTANCE TO BUILDING OWNERS OR MANAGERS, WHO OFTEN ARE COMPELLED TO PRIORITIZE HIGH-PROFILE FAÇADE ISSUES OR ROOF LEAKS ABOVE A PATCH OR TWO OF UNSIGHTLY CONCRETE. STILL, DEFERRED MAINTENANCE EVENTUALLY MEANS COSTLY REPAIRS. ONE OF THE GREATEST ISSUES RELATED TO THE DETERIORATION OF PARKING STRUCTURES IS THE CORROSION OF EMBEDDED REINFORCEMENT.

Structural concrete used in parking structures is strengthened by means of steel reinforcement bars, which are embedded into the concrete to improve resistance to tensile and compressive stresses. Ordinarily, the surrounding concrete protects this embedded steel from the corrosive effects of water and dissolved salts in the environment. However, breaches in the concrete due to cracks, flaws, thin coverage, or poor concrete consolidation can allow steel reinforcement to come into prolonged contact with corrosive elements. As the steel corrodes, it expands, leading to further damage to the concrete, greater water infiltration, and additional corrosion in a self-perpetuating cycle of deterioration. If not arrested early on, the progressive nature of the cracking and corrosion can eventually lead to an unsafe structure.

Breaches in the concrete due to cracks, flaws, thin coverage, or poor concrete consolidation can allow steel reinforcement to come into prolonged contact with corrosive elements.

Fortunately, there are preventative measures building owners, managers, and designers can take to protect against the onset of this corrosion. For garages already exhibiting signs of corrosion, various treatment options can stop the cycle of damage and restore structural integrity. Good design and construction practices are central to the prevention of reinforcement corrosion, as are products and materials that help prevent corrosive elements from reaching embedded steel. Creating favorable conditions that can overcome corrosion-inducing electrochemical reactions can also be very helpful.

By identifying early warning signs of reinforcement corrosion and responding promptly, building owners and managers can avoid or mitigate the expensive and time-consuming repairs that typically result from unchecked parking structure deterioration. (The rate at which deterioration progresses will accelerate over time.)

Corrosion of embedded steel reinforcement is a leading cause of premature deterioration in parking garages, like the one shown above.

How corrosion works

When steel is exposed to the acidic environment created by dissolved chloride salts and water, the effect is that of a giant battery. As oxygen diffuses into the concrete, it reacts with water to form hydroxide ions at the steel's surface, creating the cathode (*i.e.* negative pole of the battery).

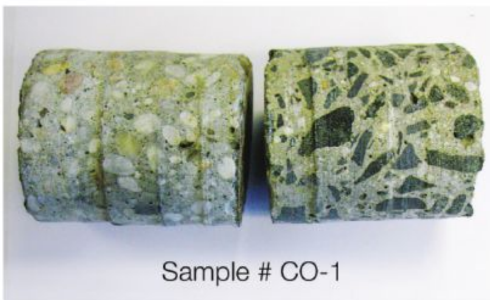
To maintain electrical neutrality, an anode forms through an oxidation reaction where positively charged iron ions migrate away from the rebar, leaving electrons behind and forming a pit in the steel. The iron ions travel toward the cathode by way of an electrolyte solution in the concrete pore structure (usually composed of dissolved chloride salts in water). The remaining negatively charged electrons then travel along the bar toward the cathode where the aforementioned hydroxide ions are formed through a reduction reaction.

Under the acidic conditions of the salt solution, the ferrous ions initially lost from the steel recombine with the hydroxide ions at the cathode to form hydrated ferric oxide (*i.e.* rust), which is deposited at the interface between the steel and the surrounding concrete. Without the presence of the electrolyte solution in the concrete, this reaction cannot occur.

As the steel corrodes, it expands up to eight times its original volume. Expansive forces cause extreme pressures within the concrete, which eventually are relieved when the concrete cracks. In turn, these cracks admit more water and chloride salts, accelerating the corrosion process, which leads to more cracking, then more corrosion, in a progressive cycle of damage. Over time, the cumulative process reduces the cross-sectional area of the reinforcing steel, compromising the parking structure's structural integrity.

Advanced corrosion results in spalls, or large chunks of concrete falling away from the structure. At this stage, deterioration is hard to ignore. Much earlier, though, the prudent building owner or manager can look for signs to identify incipient problems. Rust-colored stains at the surface of concrete can indicate corrosion below. Hairline cracks and fissures that develop over time might also be indicative of expansive stress, as an increasing volume of rust exerts pressure on the surrounding concrete. Standing water and leaks, as well as accumulated de-icing chemicals on deck surfaces, may be early warning signs of conditions conducive to corrosion.

Once corrosion has progressed to concrete delamination and exposed rebar, the cost of rehabilitation can be high. Reinforcing bar with



Core samples of concrete may be tested for chloride content, strength, and composition to guide the design professional in evaluating the structure's resistance to corrosion. Some examples are shown above.

mild corrosion may be salvaged and treated, but severely corroded steel may need to be cut out and replaced, and the concrete recast. Entire areas of the deck could require complete reconstruction, at great expense and with extensive downtime. Therefore, protecting parking decks against corrosion and treating symptoms early should be a priority.

Why rebar corrodes

High levels of calcium hydroxide in concrete make it a highly alkaline material, with a pH typically above 12.5. Values for pH ordinarily range from 0 to 14, with 0 being most acidic, 14 most basic/alkaline, and 7 being neutral. (For comparison, household bleach has a similar pH to that of concrete, while lemon juice has a pH of around 2.2.) This alkaline environment protects the embedded reinforcement by creating a passivating film around the steel. Since the electrochemical reaction of corrosion can only take place in a neutral or acidic setting, the alkaline concrete prevents steel oxidation and guards against deterioration.

Carbonation is the process by which this protective environment degrades, subjecting the reinforcement to corrosive forces. When rainwater combines with carbon dioxide in the air, it forms carbonic acid, which combines with the concrete's calcium hydroxide to form calcium carbonate. As the concentration of calcium carbonate in the concrete increases, the pH decreases, reducing the concrete alkalinity and compromising the passivating film around the embedded steel. While not a direct cause of corrosion in itself, carbonation fosters an environment that hastens the process.

Where concrete deterioration is observed, chemical analysis of the damaged concrete may be performed to measure the extent of carbonation. Water-repellent coatings or elastomeric waterproofing membranes may be applied to mitigate ongoing carbonation by preventing migration of carbonic acid into the concrete.

Moisture is essential to the corrosion process, both as an electrolyte solution and as a reagent. Water is also the vehicle by means of which acids, sulfates, or chlorides are transported into the concrete, creating an acidic environment that accelerates corrosion of embedded steel. As concrete cures, excessive mixing water not used in the hydration process can leave capillary voids in the finished product. This leads to freeze/thaw damage, where the concrete cracks and crumbles due to expansion forces of freezing water in these voids. This damage then provides a direct path for corrosive elements to reach the embedded steel.

Chloride contamination hastens corrosion by conducting electrical currents via chloride ions and accelerating the oxidation of iron atoms. Chloride intrusion also reduces the pH of concrete and destroys the passivating film around steel reinforcement. The most common source of chlorides is de-icing salt used for snow and ice removal, but those organic compounds are also present in acid rain and in the accelerators used in some older concrete structures to offset delays in strength gain and setting caused by placing concrete in cold weather.

Rebar in concrete that has undergone carbonation and de-passivation has lost the protective layer around the reinforcing steel. Therefore, it is susceptible to accelerated corrosion from even low concentrations of chlorides. Laboratory tests can measure the extent of chloride contamination as part of an investigation and repair project. (Chloride contamination above 300 ppm is generally considered the threshold that sustains active corrosion of embed unprotected reinforcing steel.)

Sufficient concrete cover over reinforcing is essential in order to protect embedded steel from water and dissolved chlorides.

Galvanic coupling contributes to corrosion through electrolytic contact between dissimilar metals. When metals with different electrical potentials come in contact in the presence of an electrolyte (*e.g.* water), metallic ions migrate from one metal (*i.e.* the anode) to the other

Installation of a traffic-bearing membrane involves multiple steps, including application of a liquid-applied coating (left) and integration of a textured wearing surface (right). The resultant membrane protects against corrosion, but requires maintenance and periodic reapplication.

(*i.e.* the cathode). The result is corrosion of the anode metal—in this case, the reinforcing steel. Electrically insulating dissimilar metals prevents galvanic corrosion, as do water-repellent coatings that prevent contact with an electrolyte. Use of sacrificial anodes of a metal more active than the reinforcing steel (*e.g.* zinc, magnesium, or aluminum) is another means of preventing corrosion due to galvanic coupling.

Implications for parking structures

The primary cause of accelerated corrosion in parking structures is the introduction of chloride-containing compounds into the concrete. Unlike other building types, parking structures are exposed directly to the elements. Further, vehicles may track de-icing salts from roads and driveways into the garage during winter, where they collect on concrete decks. Poor drainage exacerbates the problem by allowing water to pool, concentrating dissolved salt and accelerating deterioration.

De-icing chemical damage

The most common de-icing material is rock salt (*i.e.* sodium chloride), which is extremely corrosive to steel and destructive to concrete. Calcium chloride is a more effective de-icing chemical that tends to be less damaging than rock salt, but it is still a corrosive compound. Potassium chloride and magnesium chloride are better options, but they are only effective down to about −15 to −12 C (5 to 10 F), as compared with the −30 C (−20 F) minimum temperature for calcium chloride. To reduce the amount of de-icing chemical needed, property owners should apply grit/sand to increase traction, and consider a preventative application of the ice-loosening chemical calcium magnesium acetate (CMA), which does not contribute to chloride contamination.

As chloride-containing de-icing salts accumulate on parking deck surfaces, the variation in chloride ion concentration from the top to the bottom of the slab establishes a difference in electrical potential between the upper and lower rebar mats, leading to corrosion.

Progressive deterioration

Once corrosion is underway, the increase in volume from rust accumulation creates sub-surface delaminations in the concrete, as the force of expanding reinforcing steel puts stress on the surrounding material. Eventually, these forces are great enough to push off the outer face of the concrete, causing spalls to fall away and expose the reinforcing steel to further corrosive elements.

Not only are the resultant uneven surfaces unsightly, but they also serve to weaken the parking structure's structural capacity. As the reinforcing bar corrodes, it loses cross-sectional area, making it weaker and prone to breakage. The longer corrosion is allowed to persist, the more hazardous the situation becomes, until eventually the parking structure may become unstable.[1]

Controlling corrosion in new construction

Proper design and construction is the best protection against corrosion in a new parking garage. Concrete that meets American Concrete Institute (ACI) guidelines (*e.g.* ACI 318, *Building Code Requirements for Structural Concrete*) for strength, density, and quality minimizes cracks and spalls due to freeze/thaw cycling, which tend to initiate corrosion by admitting water and dissolved salts to the level of reinforcing steel. Concrete that is too porous allows chloride ions to enter through capillaries formed during curing. This can be caused by numerous issues, including too much water used during mixing or poor concrete consolidation during placement.

Sufficient concrete cover over reinforcing is crucial to protecting reinforcing bars from the elements. ACI 318-11 recommends concrete cover over reinforcing steel be at least 19 mm (¾ in.). The appropriate depth of concrete cover varies based on the type of concrete member being fabricated, the exposure to which the concrete is subject, and reinforcing bar size.

When reinforcing steel is too close to the surface, chloride ions do not need to travel far to disturb the alkaline environment of the concrete around the reinforcing bar. Moreover, the concrete surface is prone to cracking due to shrinkage and temperature differentials. Water and dissolved chlorides are more easily admitted to attack the steel when the reinforcing bar is close to the surface.

Corrosion-inhibiting admixtures can be incorporated into the concrete mix to further defend against chloride ion attack. These proprietary products work in several ways. Some may reduce the rate at which chlorides and moisture enter concrete, while others adsorb onto the reinforcing steel to form a corrosion-resistant, passivating film.

Integral waterproofing admixtures prevent water and chloride ion penetration by reducing concrete permeability and blocking the pores in the concrete matrix. Hydrophobic admixtures form water-insoluble polymers that fill voids and capillaries within the concrete. Used alone or in conjunction with permeability-reducing compounds (*e.g.* fly ash, slag, silica fume, or treated silicates), hydrophobic admixtures prevent diffusion of ions through concrete and bind to the surface of steel reinforcement, forming a protective layer. Some products may be able to self-heal hairline cracks, but larger cracks can still admit water and lead to corrosion.

Epoxy-coated rebar resists chlorides, oxygen, and moisture by providing a barrier around the steel. The coating also serves as an electrical insulator, minimizing the flow of corrosive current. Factory application involves cleaning the steel bars and applying powdered epoxy, then heating and curing at high temperatures. The downside to epoxy coating is the bars can become relatively easily damaged, so they require special handling and storage. During installation, each bar must be inspected for voids, cracks, or thin spots, as any holidays (*i.e.* discontinuities) in the coating create sites of accelerated, localized corrosion. Bent bars have less corrosion resistance than straight bars, as the coating tends to become damaged in the bend area.

Impressed Current Cathodic Protection

Painting the underside of this elevated deck prevented moisture within the slab from escaping, leading to accelerated corrosion and deterioration.

Where galvanic anodes cannot deliver sufficient current to prevent corrosion, impressed current cathodic protection (ICCP) may be used. As with passive cathodic protection, ICCP reverses the electrochemical process of corrosion through the action of an applied electric potential—in this case, the current arises not from the inherent properties of the materials themselves, as it does with galvanic coupling, but from an external power source.

However, care must be taken in designing and installing ICCP systems in parking structures. This is because excessive current density may cause the alkaline concrete to react with acid generated by the anode, leading to concrete damage.

In an ICCP system, it is difficult to provide protection at any significant distance from the anode, since current distribution within concrete is poor. Therefore, anodes must be placed no more than about 0.3 m (1 ft) apart, and the anode material must remain continuous throughout the structure. The ICCP system must take into consideration differing proportion and placement of reinforcement throughout the parking structure to avoid voltage drops from one area to another. **CS**

A team carries out the rehabilitation of corroded reinforcement and damaged concrete at a multi-story parking facility.

Assessment and repair of this university administration parking garage addressed incipient problems before deterioration could compromise the building's structural and material integrity.

Galvanized rebar applies a zinc coating to the steel reinforcement, sacrificing the zinc to electrochemical action. If the coating is damaged, it can self-heal to some degree, but galvanized rebar only resists corrosion for as long as there is zinc left to sacrifice. Avoiding galvanic coupling between coated reinforcement and uncoated steel is critical—all bars and hardware must be coated with zinc, and cut ends and welds must be coated with zinc-rich primer.

Passive cathodic protection controls steel corrosion by connecting the reinforcing bar to a sacrificial anode, a metal that is more active than steel and so corrodes preferentially. In the sacrificial metal's presence, the steel surface becomes polarized to a more negative potential, until the driving force for the oxidation of the steel is removed. The galvanic anode continues to corrode until it is consumed by the electrochemical reaction and must be replaced. Galvanized rebar is one example of passive cathodic protection, where the zinc coating acts as the sacrificial anode. Other commonly used galvanic anodes include magnesium and aluminum-based alloys.

Ultimately, a belt-and-suspenders approach to controlling corrosion in a new parking structure may be the best strategy. Sound design and construction practices are a must, and, given the expense and difficulty of treating corrosion once it is underway, it is prudent to apply multiple, complementary methods to protect against the deterioration of embedded reinforcement.

Protection of existing structures

Surface treatments are the primary means of protection for existing parking decks, as they are non-destructive and relatively straightforward to apply. Preventative coating use and prompt addressing of cracks and surface defects can avert corrosion and significantly prolong the garage's life.

Penetrating sealers enter the concrete to form a barrier that prevents water and chloride ions from migrating to the reinforcement. Typically composed of silane and/or siloxane, these treatments are vapor-permeable, allowing trapped moisture to evaporate out of the slab.[2] They are also relatively inexpensive and quickly applied, with little downtime. However, the treatments require reapplication every five years or so, and do not bridge cracks, which means corrosion can still initiate from water and dissolved salts penetrating through unrepaired openings in the concrete.

Crystalline sealers are a relatively new technology. They react in concrete to grow crystals that seal pores and micro-cracks against water intrusion. As long as moisture remains present, crystals continue to form. The crystalline sealers grow to fill new cracks as they form, reactivating in the presence of moisture to impart self-sealing properties to the concrete.

These sealers may be incorporated into new concrete as an admixture, or applied to existing structures as a surface treatment. However, because parking decks are subjected to constant movement from traversing vehicles, crystalline sealers may not be as effective as they are in other applications, as the recurring movement can break the three-dimensional array formed during the crystallization process.

Traffic-bearing membranes are elastomeric coatings that form a barrier, locking out moisture and chlorides

From proper design and construction to cathodic protection and corrosion-inhibiting admixtures, the right combination of strategies for controlling corrosion can successfully protect embedded reinforcement.

to protect the underlying concrete and reinforcement. Composed primarily of epoxy, methylmethacrylate, or urethane, traffic-bearing membranes are flexible and can bridge cracks, but they are also very expensive and require periodic recoating, as their pliability makes them susceptible to abrasion damage. The lengthy downtime for application, which can take several days, may also be a consideration.

A migrating corrosion inhibitor (MCI) can be applied to the surface of an existing concrete parking structure, as well as incorporated as an admixture into new concrete construction. In theory, a surface-applied MCI is drawn into the pores of the concrete through capillary action, penetrating down to the reinforcing steel level. Through ionic attraction, the MCI adsorbs into the steel, forming a protective coating that displaces chlorides and other corrosive compounds. In practice, however, some studies have shown the MCI may not successfully reach the steel reinforcement in some applications.[3] Preliminary research indicates vacuum and pressure-injection methods may assist in driving MCI through the concrete to the steel.

To determine which surface-applied protective treatment is right for a specific parking garage, the design professional should consider several factors, including:

- facility age;
- level of deterioration;
- chloride content;
- concrete quality;
- exposure; and
- budget.

Since the type of corrosion protection determines the maintenance demands and future treatment options in years to come, it is worth undertaking an assessment of the parking garage before settling on a product.

Corrosion remediation

For owners or managers who suspect corrosion is already underway and damage is occurring, the first step is to identify the extent of the problem. Unless corrosion is severe enough to force off the outer face of the concrete, reinforcing steel is generally hidden within the concrete slab, making any visual

ADDITIONAL **INFORMATION**

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Abstract

Parking garages are an integral part of our nation's infrastructure. Although they are subject to more deterioration than other building types, their maintenance is typically not considered of primary importance to building owners or managers, who often are compelled to prioritize high-profile façade issues or roof leaks above a patch or two of unsightly concrete. Still, deferred maintenance eventually means costly repairs. One of the greatest issues related to the deterioration of parking structures is the corrosion of embedded reinforcement. What is the solution?

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identification of early stages of corrosion difficult or impossible. Instead, the concrete is evaluated through field and laboratory testing to determine whether conditions conducive to corrosion exist within the concrete structure.

Chloride ion content testing identifies the concentration of chlorides in concrete at various depths to evaluate the probability a corrosive environment exists. Dust samples from incremental depths through the concrete slab are extracted and sent to a testing laboratory for analysis.

Half-cell potential testing determines the electrochemical behavior of embedded steel by measuring its electrical potential (*i.e.* the difference in charge from one area to the next). The greater the electrical potential, the greater the risk corrosion is occurring. Conducted onsite, the test involves removal of concrete cover over reinforcing bar, followed by the connection of exposed steel to an electrode through a voltmeter. Half-cell potential readings can be used to generate an electrical potential map, indicating areas with the greatest and least risk of corrosion.

Loss of steel reinforcement is a concern for areas where corrosion has progressed at an advanced rate. Where reinforcing bar is exposed or where concrete is cracked, delaminated, or spalled, a structural engineer should evaluate the remaining slab's structural capacity to determine whether corrosion has compromised its loadbearing ability.

Where corrosion-induced spalls have been previously repaired, a characteristic 'halo effect' might be observed, with a ring of corrosion staining appearing around the patch site. Patching delaminated and spalled concrete with conventional concrete can lead to an electrochemical reaction at the interface between the existing chloride-contaminated concrete and the new concrete. The large difference in electrical potential between the two, combined with the short distance between anode and cathode, leads to accelerated corrosion. Usually, such patches need to be repaired again in just a year or two.

Instead, spalls should be repaired using patching mortars with integral corrosion-inhibitors to protect against accelerated corrosion at the patch site. Migrating corrosion-inhibitors can also be applied to the concrete surface where testing has revealed chloride contamination and a high probability of corrosion to arrest the electrochemical process before damage becomes pronounced. Severely corroded rebar may need to be supplemented or replaced to restore structural integrity.

Choosing the right strategy

No single approach can guarantee protection against reinforcement corrosion for all parking structures. Determining the best way to prevent and treat the underlying causes of corrosion involves consideration of garage conditions and exposure, concrete quality and construction, environmental contaminants, and other factors specific to the structure and situation. Initial cost and maintenance demands are also important decision criteria.

Often, the most successful strategy involves a multi-component approach, combining preventive treatment with an ongoing program of assessment and repair specifically tailored to the structure to keep corrosion at bay.[4] Ultimately, the time and expense required to prevent corrosion and treat early warning signs is far less than that of rehabilitating a garage that has succumbed to corrosion-induced structural failure. **CS**

Notes

[1] Since the rebar expands as it corrodes, a subsurface crack will typically occur in the concrete, thereby reducing the bond strength at the crack.

[2] Silanes are often considered better for horizontal surfaces that act as wearing surfaces, as they will penetrate deeper due to smaller molecule size. However, in practice, this author finds both silanes and siloxanes need to be reapplied at roughly the same intervals. (However, this varies greatly from garage to garage, based on the amount of traffic experienced.)

[3] For example, see Stephen R. Sharp's "Evaluation of Two Corrosion Inhibitors Using Two Surface Application Methods for Reinforced Concrete Structures," published as Virginia Transportation Research Council (VTRC) 05-R16 in December 2004. Visit www.virginiadot.org/vtrc/main/online_reports/pdf/05-r16.pdf.

[4] Many jurisdictions require annual inspection of parking ramps.