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Treating Reinforcement Corrosion in Parking Structures

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Parking garages are an integral part of our nation's infrastructure. Although these structures 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 facade 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.

Corrosion of embedded steel reinforcement is a leading cause of premature deterioration in parking garages.

Structural concrete used in parking structures is strengthened by means of steel reinforcement bars, or "rebar," which is 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, whether due to cracks, flaws, thin coverage, or poor concrete composition, 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.

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

By identifying early warning signs of reinforcement corrosion and responding promptly, building owners and managers can avoid or mitigate the

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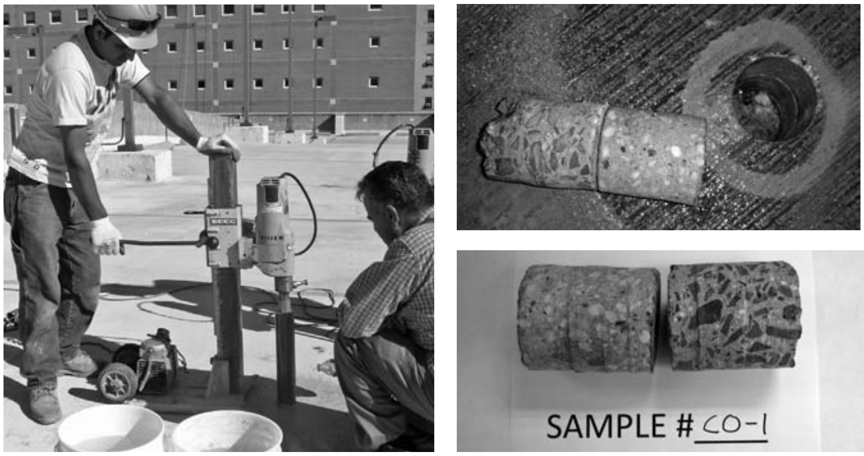


Core samples of concrete may be tested for chloride content, strength, and composition to guide the design professional in evaluating the structure's resistance to corrosion.

expensive and time-consuming repairs that typically result from unchecked parking structure deterioration.

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 surface of the steel, creating the *cathode*, or negative pole of the battery. At the *anode*, the positive pole, iron ions migrate away from the rebar, leaving a pit in the surface, and travel toward the cathode by way of an electrolyte solution, usually composed of dissolved chloride salts in water. Under the acidic conditions of the salt solution, these iron ions combine with the hydroxide ions at the cathode to form hydrated ferric oxide, or rust, which is deposited at the interface between the steel and the surrounding concrete.

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. These cracks in turn admit more water and chloride salts, accelerating the corrosion process, leading 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 structural integrity of the parking structure.

Advanced-stage corrosion results in *spalls*, or large chunks of concrete falling away from the structure, which make deterioration hard to ignore. Well before that, though, there are signs the prudent building owner or manager can look for to identify incipient problems. Rust-colored stains at the surface of concrete can indicate corrosion below the surface. 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 deicing chemicals on deck surfaces, may be early warning signs that conditions conducive to corrosion are present.

Once corrosion has progressed to the point that concrete is delaminating and rebar is exposed, the cost of rehabilitation can be high. Reinforcing bar with 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 may need to be completely reconstructed, at great expense and with extensive down-time. Therefore, protecting parking decks against corrosion and treating symptoms early should be a top 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 oxidation of the steel 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 calcium hydroxide in concrete to form calcium carbonate. As the concentration of calcium carbonate in the concrete increases, the pH decreases, reducing the alkalinity of the concrete and compromising the passivating film around the embedded steel. While not a direct cause of corrosion in itself, carbonation fosters an environment that hastens corrosion.

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 that is 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 current 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 deicing salt used for snow and ice removal, but chlorides 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 and is therefore 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.

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, such as water, metallic ions migrate from one metal, the anode, to the other, the cathode. The result is corrosion of the anode metal, in this case, the reinforcing steel. Electrically insulating dissimilar metals prevents galvanic corrosion, as does the use of water-repellent coatings that prevent contact with an electrolyte. Use of sacrificial anodes of a metal that is more active than the reinforcing steel, such as 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, and, during the winter months, vehicles track deicing salts from roads and driveways into the garage, where they collect on concrete decks. Poor drainage exacerbates the problem by allowing water to pool, concentrating dissolved salt and accelerating deterioration.

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

Deicing Chemical Damage

The most common deicing material is rock salt (sodium chloride), which is extremely corrosive to steel and destructive to concrete. Calcium chloride is a more effective deicing 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 5 to 10°F, as compared with the -20°F minimum temperature for calcium chloride. To reduce the amount of deicing 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 deicing 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*, or broken chunks of concrete, to fall away, exposing the reinforcing steel to further corrosive elements. Not only are the resultant uneven surfaces unsightly, they serve to weaken the structural capacity of the parking structure. 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.

Controlling Corrosion in New Construction

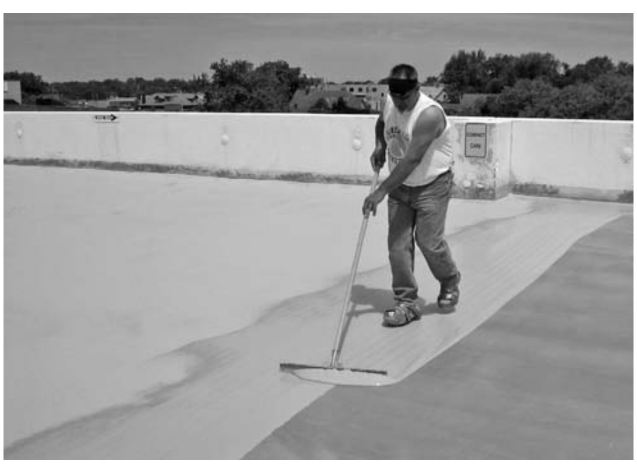
Proper design and construction is the best protection against corrosion in a new parking garage. Concrete that meets American Concrete Institute guidelines for strength, density, and quality minimizes cracks and spalls due to freeze/thaw cycling, which tend to initiate corrosion by admitting water and 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 a number of issues, including too much water used during mixing or poor consolidation of the concrete during placement.

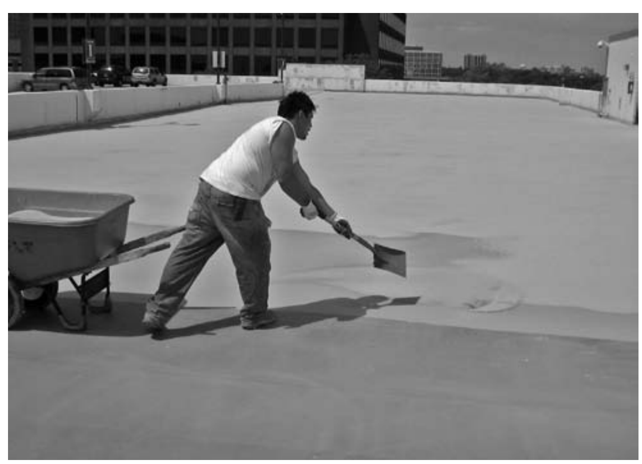
Sufficient concrete cover over reinforcing is crucial to protecting reinforcing bars from the elements. The American Concrete Institute recommends that concrete cover over reinforcing steel be at least ¾ inch. In practice, however, the appropriate depth of concrete cover varies based upon factors such as the type of concrete member being fabricated, the exposure to which the concrete is subject, and the size of the reinforcement bars. 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 top surface of concrete is prone to cracking due to shrinkage and temperature differentials, and will more easily admit water and dissolved chlorides in to attack the steel if 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 a number of different 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 like 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 that the bars can become damaged relatively easily, so they require special handling and storage. During installation, each bar must be inspected for voids, cracks, or thin spots, as any holidays 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.





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.

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 will corrode preferentially. In the presence of the sacrificial metal, 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 will continue 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, complimentary methods as appropriate to protect against the deterioration of embedded reinforcement.

Impressed Current Cathodic Protection

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. Care must be taken in designing and installing ICCP systems in parking structures, however; 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 a foot 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, so as to avoid voltage drops from one area to another. ■

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. Using coatings preventatively and addressing cracks and surface defects promptly can prevent corrosion and significantly prolong the life of the garage.

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, and they are relatively inexpensive and quickly applied, with little downtime. However, they require periodic reapplication every five years or so, and they don't bridge cracks, which means that corrosion can still initiate from water and dissolved salts that penetrate through unrepaired openings in the concrete.

Crystalline sealers are a relatively new technology, which 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 advantage of crystalline sealers is that they will grow to fill new cracks as they form, reactivating in the presence of moisture to impart self-sealing properties to the concrete. Crystalline 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 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. Lengthy downtime for application, which can take several days, may also be a consideration.

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, when surface applied, MCI is drawn into the pores of the concrete through capillary action, penetrating down to the level of the reinforcing steel. 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 that MCI may not successfully reach the steel reinforcement in some applications; preliminary research indicates that vacuum and pressure-injection methods may assist in driving MCI through the concrete to the level of the steel.

To determine which surface-applied protective treatment is right for your parking garage, the design professional will consider a number of factors, including age of the facility, level of deterioration present, chloride content, concrete quality, exposure, and budget. Since the type of corrosion protection applied now will determine the maintenance demands and future treatment options in years to come, it's worth undertaking an assessment of the parking garage before settling on a product.

Corrosion Remediation

For owners or managers who suspect that 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 visual 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.

Half-cell potential readings can be used to identify areas of reinforcing steel that are at greatest risk of corrosion.

Chloride ion content testing identifies the concentration of chlorides in concrete at various depths, in order to evaluate the probability that 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, or the difference in charge from one area to the next. The greater the electrical potential is, the greater the risk that corrosion is occurring. Conducted on-site, the test involves removal of concrete cover over reinforcing bar, then 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 those 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 structural capacity of the remaining slab to determine whether corrosion has compromised its load-bearing capacity.

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 will 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 surface of concrete where testing has revealed chloride contamination and a high probability of corrosion, in order to arrest the electrochemical process before damage becomes pronounced. Severely corroded rebar may need to be

(continued on page 8)

representative projects

Concrete Parking Structures

Preventing deterioration of embedded steel is critical to the longevity of reinforced concrete garages. Without adequate protection from the harmful effects of water, ice, salt, and snow, metal reinforcement corrodes, leading to serious damage if left unchecked.

To address corrosion-related deterioration, Hoffmann Architects develops parking garage solutions that restore concrete integrity while protecting against future problems.

We have provided parking garage evaluation, maintenance, and rehabilitation services for diverse structures, including:

General Re Headquarters
Stamford, Connecticut
Garage Repair and Maintenance Program

West*Group Corporate Campus
McLean, Virginia
Investigation of Four Garages

Hospital of Central Connecticut
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Garage Rehabilitation

Cromwell Towers
Yonkers, New York
Garage Rehabilitation

Constitution Plaza
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Plaza and Garage Rehabilitation

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MacDougall-Walker Correctional Institution
South Suffield, Connecticut
Garage Engineering Analysis

Northeast Utilities
Berlin, Connecticut
Garage Assessment and Repair Design

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Hartford, Connecticut
Garage Assessment and Repair

One Washingtonian Center
Gaithersburg, Maryland
Garage Repair Program Design

New Haven Correctional Center
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Town Center
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Annual Garage Investigation and Repair

Seneca Niagara Casino and Hotel
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Garage Rehabilitation

New Haven City Hall
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State University Construction Fund in Albany, New York. *Garage Assessment/Repair.*

Columbia University Engineering Terrace
New York, New York
Garage Consultation and Repair Design

Middlesex Hospital
Middletown, Connecticut
Garage Rehabilitation

Bushnell Tower
Hartford, Connecticut
Garage and Plaza Assessment

State University of New York Downstate Medical Center
Brooklyn, New York
Garage Assessment and Repair

Washington Gas Springfield Operations Center in Springfield, Virginia. *Garage Assessment.*

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(continued from page 6)

supplemented or replaced to restore structural integrity.

Choosing the Right Strategy

No one 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, one which combines preventive treatment with an ongoing program of assessment and repair to keep corrosion at bay. Ultimately, the time and expense required to prevent corrosion and treat early warning signs is far less than that of rehabilitating a garage that succumbs to corrosion-induced structural failure. ■

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