

# DETERIORATION OF REINFORCED CONCRETE ELEMENTS

By Matthew D. Pritzl, EIT

Why is it that buildings constructed with concrete thousands of years ago (*Figure 1*) have withstood the test of time, while buildings constructed with reinforced concrete within the last 100 years have deteriorated rapidly (*Figure 2*)?

The answer is...corrosion of the reinforcing steel within reinforced concrete. Concrete, by itself, is a material with high compressive strength and low tensile strength. Steel, a material that is strong in tension as well as compression, is used as tension reinforcement for concrete. By adding steel reinforcement to concrete, reinforced concrete (R/C) becomes a versatile construction material.

Compared to other construction materials, properly constructed R/C elements have a long service life. When constructed properly, high-quality concrete is an ideal environment for reinforcing steel. The ce-

ment paste within the concrete creates a passive, highly alkaline environment (pH of 12 - 14) that affords corrosion protection to the uncoated steel. This occurs as a surface oxide film is formed on the rebar. As long as the integrity of the protective film is maintained, the steel will remain in a passive

and protected state.

When uncoated steel is exposed to moisture and oxygen, corrosion will occur (think of the metal chair and swing set in your backyard). The protective film, however, will protect the reinforcing steel in the presence of moisture and oxygen. Nevertheless, dete-



*Figure 1 - Pantheon in Rome, Italy, constructed in 125 A.D.*



*Figure 2 - Deterioration of reinforced concrete beam element constructed in the 1960s.*



**Figure 3 – Lack of concrete cover.**

rioration of R/C elements can be accelerated by defects that break down the protective layer. These defects are introduced into the concrete before or at the time of construction.

The defects stem from design and construction faults. Design faults include a lack of adequate drainage in horizontal members, a lack of concrete cover that protects the steel reinforcement, and inappropriate concrete mixes. Construction faults

the protective film and provide conditions favorable for the corrosion of the reinforcing steel. Carbonation and chloride contamination are the two main processes that break down the protective film. Once the protective film is broken down, corrosion will commence in the presence of moisture and oxygen.

As corrosion occurs, the corrosion by-products expand the size of the steel and produce large stresses on the concrete.



**Figure 4 – Cracks in concrete.**

include failure to provide the design concrete cover (Figure 3), inadequate compaction, improper placement techniques, and lack of cold joints.<sup>5</sup>

The aforementioned design and construction faults allow for the ingress of harmful chemicals that break down

These stresses are relieved in the form of cracks (Figure 4), delaminations (planes of cracking within the concrete), and spalls (Figure 5).

Concrete mixes used in the past were highly permeable and allowed for the ingress of atmospheric gases, moisture, and salt. Carbonation occurs when carbon dioxide from the atmosphere diffuses through the porous concrete and neutralizes the alkalinity of the concrete. Over a period of time, the carbonation process reduces the alkalinity of the concrete to a pH of 8 or 9, where the oxide film is no longer stable.

To determine the depth of carbonation, a phenolphthalein solution is applied to a concrete sample. The solution is colorless at and below a pH of 8.2 and pink at pH levels above 10.0 (Figure 6).<sup>2</sup> A common problem occurs when the depth of carbonation is greater than the concrete cover provided for the reinforcing steel. When this occurs, the protective layer is destroyed and the reinforcing steel no longer has protection against moisture and oxygen.

As mentioned previously, chloride contamination also breaks down the protective layer and initiates the corrosion process. Now, you might be saying to yourself, “I have a structure in the Midwest. I’m not on a bridge, so I don’t have deicing salts, and I’m not anywhere near saltwater. How can my structure be affected by chlorides?” The answer is that chlorides can be introduced to the concrete during the mixing process or in service. In the past, calcium chloride was used as an admixture to accelerate the curing time of concrete. It allowed the placing of concrete in cold conditions and provided



**Figure 5 – Spalls in concrete.**

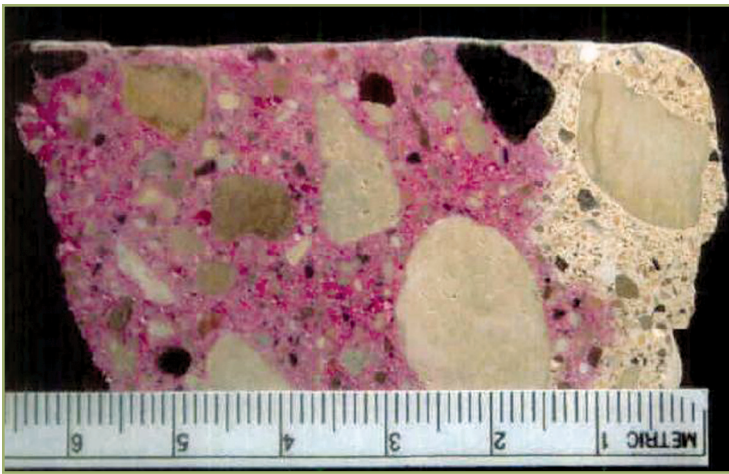


Figure 6 - Depth of carbonation sample.

higher early-strength concrete that allowed formwork to be stripped earlier. Chlorides can also be found in the mixing water or aggregates. In service, chloride contamination occurs because of the use of deicing salts, proximity to seawater, and groundwater salts. Parking structures also have significant deterioration because of the use of deicing salts. What's more, take notice of the concrete floor that makes up the entry to a building. Chances are that salts carried in from outside have entered the concrete, and spalls or cracking have occurred there.

The accepted corrosion threshold for chloride content in concrete is minimal, approximately 0.025%

- 0.0375% chloride ions by weight of concrete (1.0 to 1.5 lb chloride ions/yd<sup>3</sup> of concrete). Generally speaking, this means that approximately two pounds of salt (NaCl) for every cubic yard of concrete (3915 lb) is needed to initiate corrosion! Furthermore, accelerated corrosion that leads to rusting of the steel and spalling of the concrete has been found to occur at 3 lb/yd<sup>3</sup>, and significant loss of steel has been found to occur at levels in excess of 7 lb/yd<sup>3</sup>.<sup>4</sup>

Chloride content can be calculated by taking powder samples from the concrete. These samples are then brought to the laboratory and mixed with an extraction liquid to determine the chloride content. In locations with premixed chlorides, content will be fairly uniform. In areas of service chlo-

ride contents even lower than the threshold mentioned above can induce corrosion.<sup>4</sup>

Although depth of carbonation and chloride content are indicative of corrosion activity, it is not truly a measure of actual corrosion activity. Half-cell potential testing is one way to estimate the corrosion activity

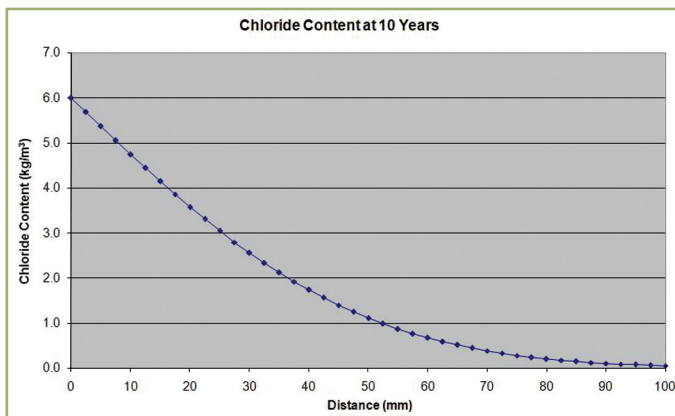


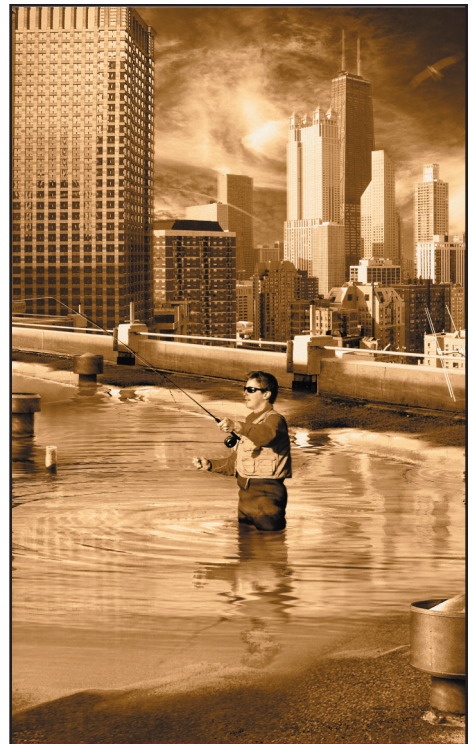
Figure 7 - Profile of service chloride content vs. depth.

of the reinforcing steel. Half-cell potentials measure the difference in potential between a reference electrode (copper-copper sulfate) and the reinforcing steel (Figure 8). Potential readings more negative than -350 mV indicate a 90% probability of corrosion activity, readings between -200 mV and -350 mV indicate an unknown probability of corrosion activity, and readings more positive than -200 mV indicate a 90% probability of no corrosion activity.<sup>1</sup>

A simple way of locating areas of corroded reinforcing steel is to "sound" the concrete. This method requires the use of a rock hammer on a vertical plane or a chain on a horizontal plane. By impacting the concrete through the striking of the hammer or dragging of the chain, a tone that

ride contamination, a profile of chloride content vs. depth can be made by taking samples at regular intervals of depth (Figure 7).

To further complicate things, carbonation and chloride contamination can work together. As the pH of concrete is lowered through carbonation, chlo-



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sounds “hollow” can be heard. Even though the area appears to be in good condition, the difference in tone reveals that areas of distress lie below the concrete surface (Figure 9).<sup>2</sup>

Now that we have a brief understanding of the causes of corrosion and ways of assessing the level of corrosion activity in a structure, how do we fix the problem? The answer is...there is no simple answer.

Once the corrosion process has begun, it is difficult to produce a long-term repair to the areas of deterioration unless the underlying problem, corrosion of the reinforcing steel, is addressed. Before getting into specifics on repair options, let's first discuss the corrosion process.

Corrosion is electrochemical in nature; it is essentially a battery in which electrical current flows between an anode and a cathode (Figure 10). The anode is the site where corrosion occurs.

Differing electric potentials may be located on the same piece of reinforcing steel (Figure 11) because of the heterogeneous nature of steel (it is created from iron ore), depth of carbonation, chloride content, concrete imperfections, cracks, etc. The pore water in the concrete is the electrolyte that conducts the electricity.<sup>4</sup>

Conventional patch repair requires the removal of distressed concrete to a distance of approximately three-quarters of an inch behind the reinforcing steel, cleaning of the rebar, and patching of the area with new material. Although this method may work in nonchloride-contaminated concrete, the same procedure has a potential to increase corrosion activity in chloride-contaminated concrete.

In a patch repair with chloride-contaminated concrete, the newly repaired (chloride-free) area has a drastically different electrical potential than the nonrepaired (chloride-contaminated) area. (On a side note, another problem with chloride contamination is that the chloride ions are not consumed and that they continue to fuel the corrosion cell.) The newly repaired area acts as a noncorroding cathode, while the old area becomes a corroding anode (Figure 12). This results in an accelerated corrosion cell near the patch. The “ring-anode” or “halo” effect can be seen when spalls appear next to previously patched areas. It is not uncommon for additional repairs to be made at these

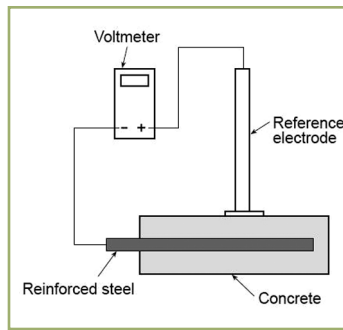


Figure 8 - Schematic of half-cell potential test.<sup>1</sup>

areas after only two to five years.<sup>3</sup>

For large areas of deterioration with significant levels of chloride concentration, removal and replacement may be a more economical and aesthetically pleasing alternative to patch repair.<sup>4</sup>

Another approach is to apply sealers and coatings. While they help delay the onset of corrosion when applied before exposure to service conditions, they have limited effectiveness when applied after the onset of corrosion.<sup>3</sup> Another type of product used is a corrosion inhibitor. These products are applied to the concrete surface after exposure to service conditions and seek out the reinforcing bars within the concrete. Testing and research on such products, however, has shown mixed results, as their effectiveness is dependent on the chloride content. When chloride content exceeded 0.05% chloride ions by weight of concrete (two times the threshold), corrosion inhibitors were ineffective.<sup>6</sup>

The only rehabilitation technique that can prevent cor-

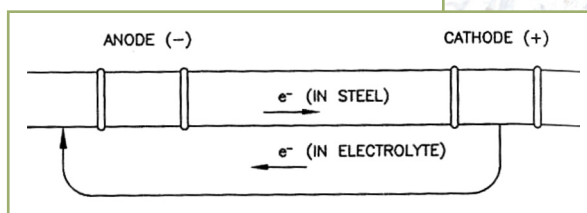


Figure 10 - Corrosion cell.<sup>4</sup>

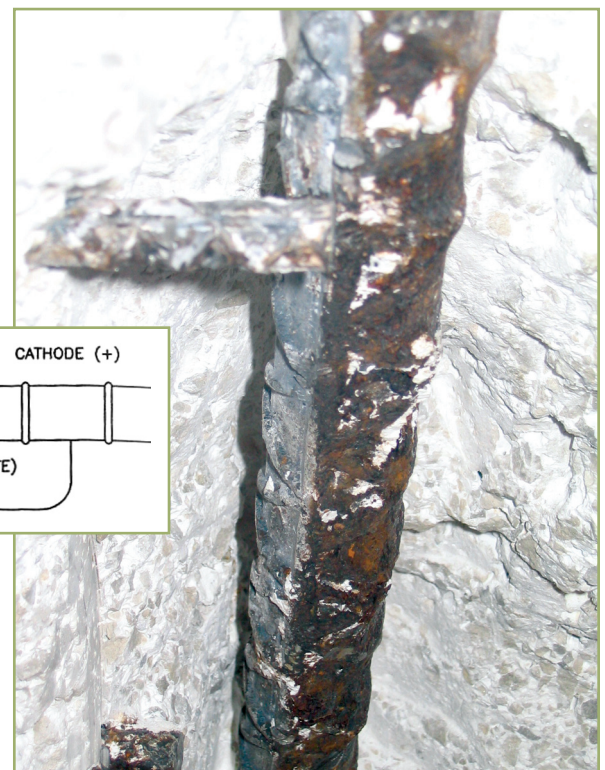
Figure 11 - Corrosion on same piece of reinforcing steel.



Figure 9 - Area of distress discovered by sounding.

rosion activity in chloride-contaminated concrete is Cathodic Protection (CP).<sup>7</sup> By connecting the reinforcing steel to a sacrificial anode or an impressed current, the reinforcing steel effectively becomes a non-corroding cathode. Simply stated, CP reverses the corrosion process.

As indicated, there are two types of CP systems - the galvanic (sacrificial) system and the impressed current system (ICCP). The galvanic anode system utilizes a sacrifi-



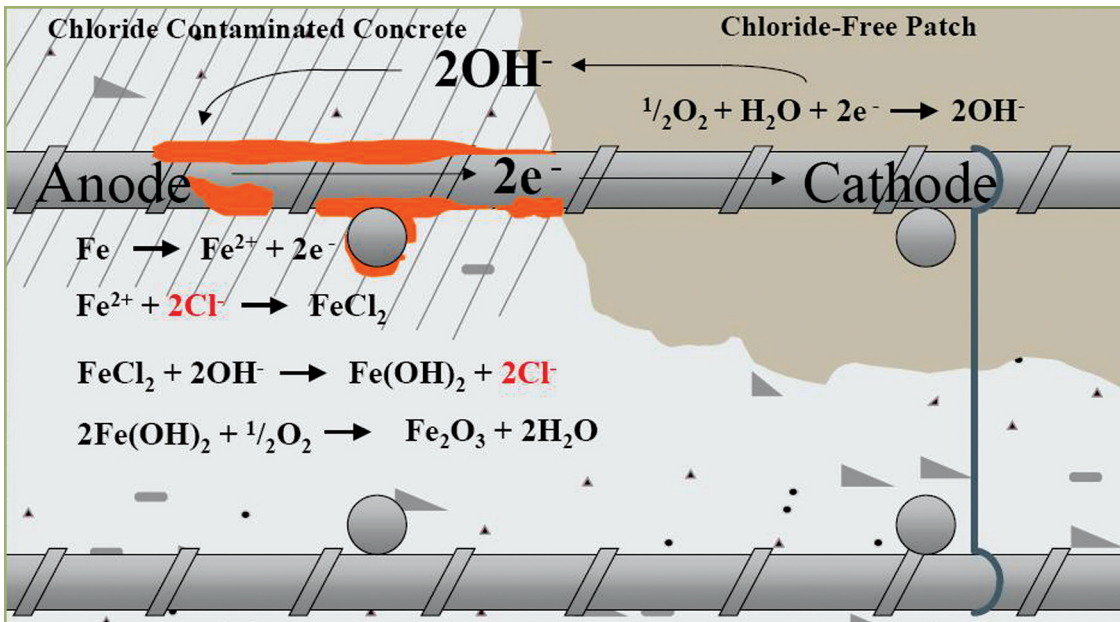


Figure 12 - Patch accelerated corrosion.<sup>3</sup>

cial metal, such as zinc, to create a current flow from itself to the rebar. When attached to the reinforcing steel, the anode supplies an electric current and protects the reinforcing steel by sacrificing itself. Galvanic anodes can be attached to the rebar and embedded in the concrete (Figure 13) or sprayed on the concrete surface (Figure 14). In the latter case, a connection is made between the sprayed metal and the rebar.

ICCP systems (Figure 15) utilize anodes connected to an external DC power source that supply the necessary current to



Figure 13 - Installation of an embedded sacrificial anode.

convert the reinforcing steel to a cathode. ICCP systems can also be embedded in the concrete or sprayed on the concrete surface. Another system attaches a mesh that is covered in a concrete overlay to the concrete surface.

Sacrificial CP systems, with no monitoring or maintenance, have a 15-year useful life. ICCP systems, which require monitoring and maintenance, have useful lives of 25+ years.

Another method is to use electrochemical chloride extraction (ECE) (Figure 16). This procedure applies an electric field between the reinforcing steel and an externally mounted mesh. During this short duration treatment, the chloride ions migrate away from the reinforcing steel and toward the mesh. This mesh is removed

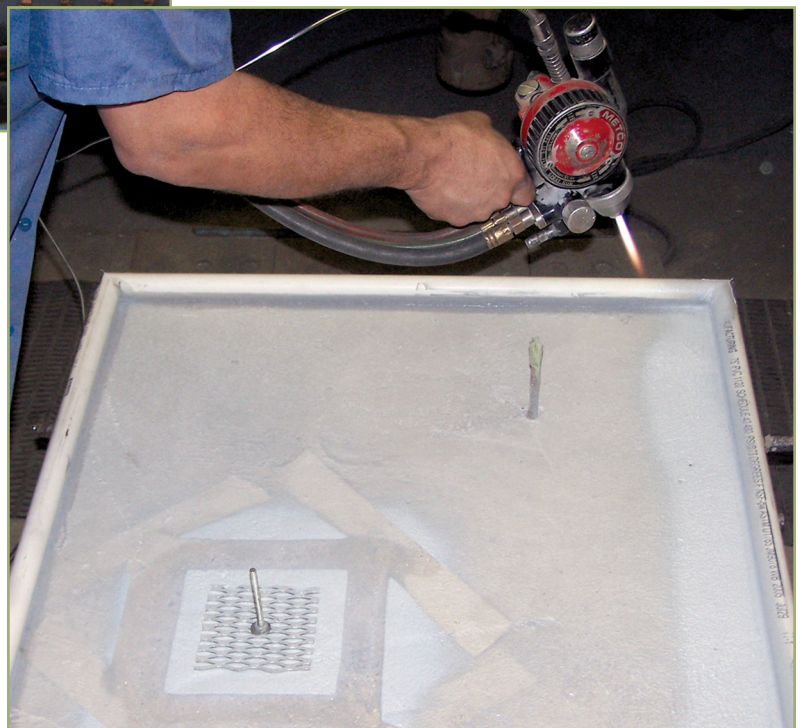


Figure 14 - Application of a thermal sprayed sacrificial anode

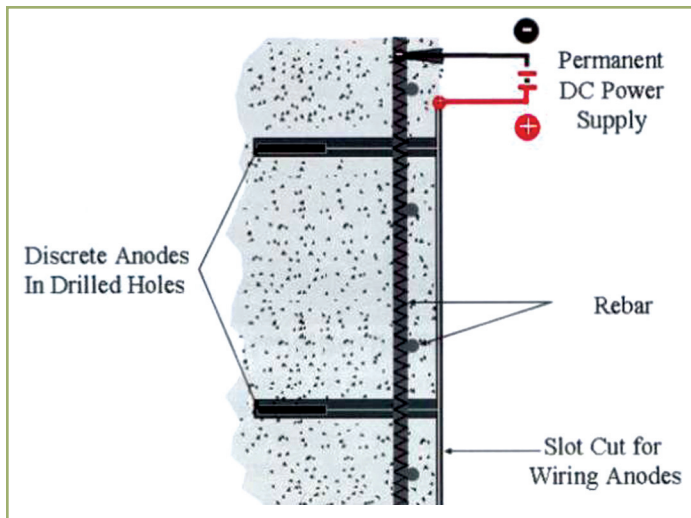



Figure 15 - Schematic of an ICCP system.<sup>3</sup>

after treatment. Additionally, the protective layer around the reinforcing steel is regenerated.<sup>3</sup>

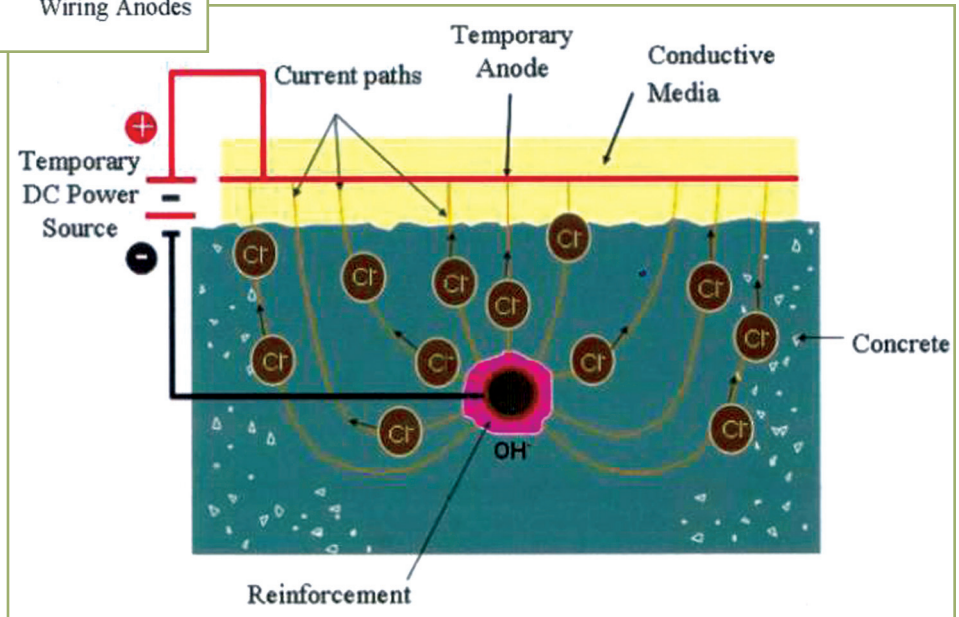
Although CP and ECE are effective in chloride-contaminated concrete, a process called realkalization is effective for carbonated concrete. Similar to ECE, an electric field is applied between the reinforcing steel and the mounted mesh. The difference is that an electrolyte is transported into the concrete. This electrolyte restores the alkalinity of the concrete and reinstates a passive environment for the reinforcing steel.<sup>3</sup>

Although many alternatives exist for the rehabilitation of deteriorated concrete elements, each project will have a different solution. Additionally, each repair option has its own advantages and disadvantages. Therefore, the options of repair will vary on a project-by-project basis. 

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Figure 16 - Schematic of an ECE system.<sup>3</sup>



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#### Matthew D. Pritzl, EIT

Matthew D. Pritzl, EIT, is a project manager at Inspec, Inc., in Milwaukee, WI. His work duties include the evaluation and repair/rehabilitation of exterior walls. He has received B.S. degrees in architectural studies (magna cum laude) and civil engineering (summa cum laude) from the University of Wisconsin-Milwaukee (UWM). Mr. Pritzl is also finishing his M.S. in engineering (structures) at UWM and conducting a thesis project sponsored by the Wisconsin Department of Transportation that studies the "Evaluation of Methods of Rebar Protection, Spall Prevention, and Repair Techniques on Concrete Girders."

