



Corrosion Manual

Solutions and Strategies for Corrosion Mitigation



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Corrosion Mitigation

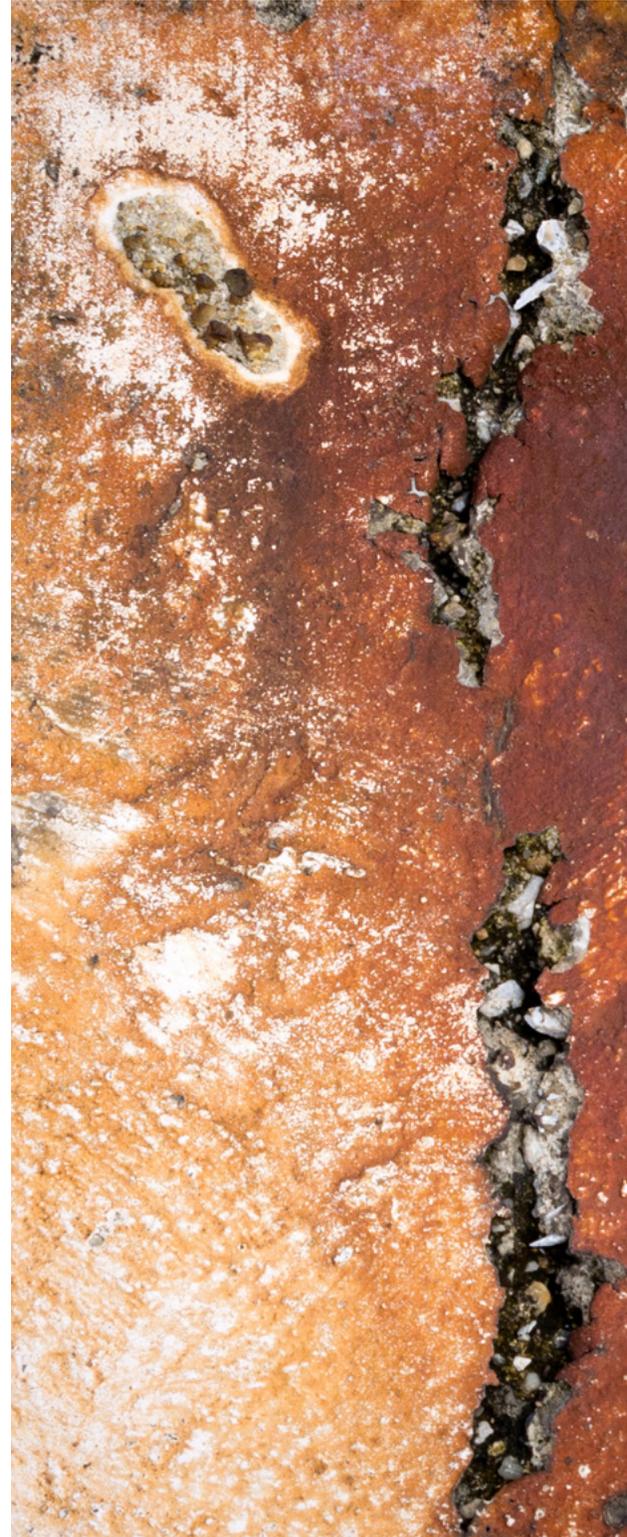
Corrosion of reinforced concrete structures is a complex issue that can be initiated by a variety of different mechanisms. In order to successfully mitigate corrosion one must have a fundamental understanding of what causes corrosion to occur as well as how to best address each root cause.

The effects of corrosion are both widespread and extremely costly. Corrosion affects all types of structures, including but not limited to infrastructure, commercial and residential buildings, parking structures, industrial facilities, pipelines, and treatment plants. The Strategic Development Council, a group of several industry organizations associated with concrete and concrete repair, has estimated that the annual cost of repairing concrete ranges from \$18-21 billion per year (14). While not all of these repairs are directly related to the corrosion of reinforcing steel, many of them are caused by or will lead to corrosion if not addressed. The economic impact of corrosion cannot be ignored, and it is essential that structures are properly constructed and maintained to prevent or reduce the onset of corrosion.

In addition to the immense economic cost associated with corrosion, society also bears the personal costs associated with degradation of concrete structures. According to the American Society of Civil Engineers (ASCE), 26% of the nation's bridges are either structurally deficient or functionally obsolete with an average age of 43 years (3). While functionally obsolete bridges are classified as such due to exterior factors not involving corrosion, structurally deficient bridges are often the direct result of corrosion. Severe degradation of steel reinforcing in concrete bridges may lead to a reduction in the load carrying capacity of the bridge. With reduced capacity, many of these roadways must be closed to traffic or certain classes of vehicles due to the risk of structural failure. This adds additional economic costs due to increased travel time and/or distance for commercial vehicles, but also leads to traffic disruptions and congestion for the general public.

The effects of corrosion, whether they are financial, structural, or simply a burden to society, are clearly a significant issue in the construction industry. In an effort to curb these costs and effects, many technologies, systems, and strategies are being developed by the industry. Just as corrosion is a far-reaching and widespread issue, so too are the solutions being developed to combat it. There are a wide variety of different technologies available, and it is essential to understand the root cause of the corrosion in order to utilize the correct solution.

This manual will explore the basics of the corrosion process and introduce the various mitigation strategies available from Master Builders Solutions which may be used to reduce or prevent the effects of corrosion. The technical details of the various strategies will be discussed along with the advantages and disadvantages of each. The manual will also provide information regarding proper installation of various technologies which is a crucial factor in achieving a high quality, high performance repair. In addition to basic system information, this manual will also offer insight into selecting the proper system for various field scenarios. Corrosion mitigation technologies are unique in their performance and can be more useful in certain situations than others. The manual will provide the information necessary to ensure that the correct Master Builders Solutions corrosion mitigation system is used for the various applications that would require them. By providing the information, tools, and knowledge required to adequately address corrosion issues, this manual will assist in the decisions required to achieve a high quality and long lasting repair.



Corrosion Basics

Definition Of Corrosion

Corrosion of reinforcing steel in concrete is defined by the International Concrete Repair Institute (ICRI) as the destruction of metal by chemical, electrochemical, and electrolytic reaction within its environment (8). In the case of reinforced concrete, the iron atoms that comprise the steel reinforcement provide the metal and the concrete and atmospheric conditions serve as the environment. Chemical changes within the concrete due to the presence of chlorides, carbonation, or chemical attack all can lead to corrosion of the reinforcing steel.

Oxidation

Regardless of the root cause, corrosion of reinforcing steel is ultimately due to oxidation of the iron. Oxidation refers to the loss of at least one electron when two different substances interact. Due to its molecular structure, iron atoms readily yield electrons to ions that more readily accept electrons. Oxidation of iron in reinforced concrete is due to the presence of both water and oxygen. The process involves a series of reactions which lead to the formation of iron oxide, more commonly known as rust. The chemical equation below demonstrates oxidation of an iron atom, with the iron atom breaking down to a positively charged iron ion and yielding two free negatively charged electrons.



Reduction

Reduction is the opposite of oxidation. When a substance is reduced, it means that it has gained electrons via a chemical reaction. In terms of corrosion of reinforced concrete, reduction occurs in the oxidation of the iron atoms. The free electrons that become available after the iron is oxidized bond with oxygen and water to form negatively charged hydroxide ions. This topic will be explored in greater detail on the following pages.

Electrochemical Reaction

An electrochemical reaction is a chemical reaction between substances that involves the transfer of electrons between the substances to generate an electric current, also known as an oxidation-reduction or redox reaction. In the case of corrosion, the potential (or charge buildup of electrons or voltage) is generated via the oxidation of the iron atoms into iron oxides. The current generated is referred to as the corrosion current, and the rate at which it flows determines the corrosion rate of the reinforcing steel.

Electrical Resistivity

Electrical resistivity is defined by ICRI as a measure of the resistance of a material to flow of electric current (8). When discussing corrosion in concrete the electrical resistance of the concrete is one of the controlling factors of the rate of corrosion. Resistivity is a material property. A material with a certain resistivity will produce a certain resistance depending on the available cross-sectional area and length the current has to flow. As the resistivity of the concrete cover increases (such as when the cement hydrates or the concrete dries out) it becomes more difficult for the corrosion current to pass through. This is a natural defense mechanism of the concrete which can be improved with the use of some types of corrosion mitigation technologies to be discussed in greater detail later in the manual.

Anode

ICRI defines an anode as the electrode in electrolysis at which negative ions are discharged, positive ions are formed, or other oxidizing reactions occur (8). It is the part of a corrosion cell in reinforced concrete where the iron-oxide forms on the reinforcing steel. Corrosion is an oxidation process in which the iron atoms lose electrons and react with oxygen and water to form rust. Figure 1 below depicts the formation of rust on the surface of a segment of reinforcing steel. The reddish orange material is the iron oxide, or rust, formed as a result of the electrochemical corrosion reactions.



Figure 1 – Rust Formation on Reinforcing Steel

Cathode

The cathode is the part of the corrosion cell where no visual change is seen on the reinforcing steel. As defined by ICRI, it is the electrode at which electrons are consumed and chemical reduction occurs (8). No physical change occurs at the cathode in reinforced concrete. It is simply the location where hydroxides form. The cathode is frequently located immediately adjacent to the anode, which is why we often see badly corroded steel adjacent to clean steel.

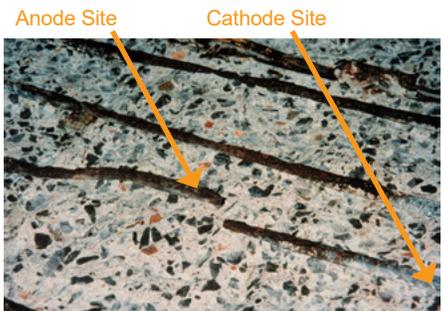


Figure 2 – Anodic and Cathodic Sites on Corroded Reinforcing Steel in Concrete in a Corrosion Cell in a Reinforced Concrete Structure

Types of Corrosion

When considering corrosion of all metals, there is a large number of different types of corrosion. When looking exclusively at corrosion of steel in reinforced concrete, the two types that occur most frequently are forms of macrocell and microcell corrosion. Macrocell corrosion is indicated by highly aggressive and localized corrosion at a small anode which leads to pitting of the steel at isolated locations. Microcell corrosion on the other hand includes the formation of large anodes that may span long lengths of the reinforcing steel. While microcell corrosion is not as detrimental to reinforcing steel, its rate of occurrence must be monitored to ensure adequate structural capacity of the reinforced concrete structure.

Pitting Corrosion

Pitting corrosion is the localized, deep deterioration of metal surfaces. We often observe pitting of reinforcing steel due to the localized formation of anodes on the reinforcing steel. Corrosion will aggressively occur at the anode, resulting in deep pits in the steel. The cathode typically forms in an area in close proximity to the anode though it can be distributed over fairly large areas. At the cathode location corrosion of the steel does not occur and the bar retains its original shape. Pitting corrosion is a serious concern as it can result in complete degradation of the reinforcing steel at a localized area, ultimately leading to a break in the reinforcing steel and loss of continuity. When left unchecked, pitting corrosion can severely impact the strength capacity of a structure and cause unexpected failures of structural members.



Figure 3 – Pitting Corrosion of Reinforcing Steel

Galvanic Corrosion

Galvanic corrosion usually does not lead to corrosion of the reinforcing steel itself; however its principles are used by some of the corrosion mitigation technologies included in this manual. Per ICRI, galvanic corrosion is accelerated corrosion of a metal because of an electrical contact with a more noble metal or a more noble non-metallic conductor in a corrosive electrolyte (8). When reinforcing steel is electrically connected to a less noble metal such as zinc, galvanic corrosion of the zinc occurs. Galvanic corrosion does not simply occur because the zinc is attached to the steel however. Halogens must be present in concentrations exceeding the corrosion threshold in order to initiate the process, typically chlorides in reinforced concrete. The chart to the right (Fig. 4) lists many of the common metals in order of nobility.

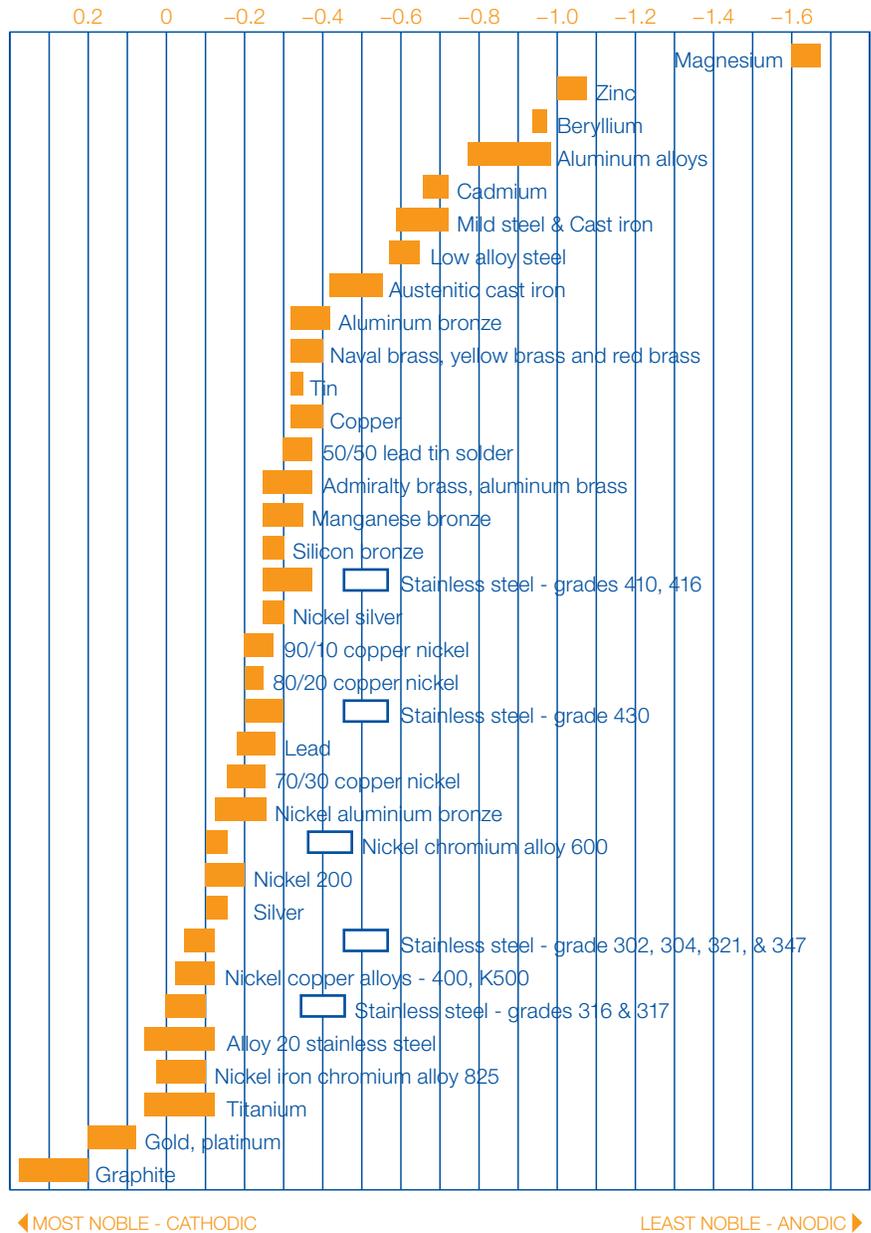


Figure 4 – Electromotive Series in Order of Most Noble (Left) to Least Noble (Right) (5)
**Note that the order will change slightly depending on the environment of the corrosion cell. The effects of this can be seen in a related chart called the galvanic series which is not included in this document.

Causes of Corrosion in Concrete

Chloride Induced Corrosion

Chlorides are the most common cause of corrosion in reinforced concrete structures. There are several sources for chloride exposure to concrete, typically road salts in northern climates and ocean sea spray along coastal areas. In addition to these external sources, chlorides have in the past been included as components of admixtures in fresh concrete. While the use of chlorides in admixtures is now typically restricted, older concrete mix designs often contained admixtures which included chloride concentrations above the corrosion threshold. Current American Concrete Institute (ACI) code requirements limit the maximum water-soluble chloride ion content in new concrete to 1% or less depending on exposure class and type of reinforcement used (2). This addition to the concrete code was made as the devastating effects of chlorides in concrete have become better understood.

Chloride induced corrosion occurs in concrete when the chloride concentration exceeds the corrosion threshold or there is a loss of alkalinity in the concrete. There is much debate about what the exact corrosion threshold level is in reinforced concrete. Every concrete mix is unique, and changes in the density, air content, admixtures, and aggregate can drastically alter the performance of a mix. Thus it is difficult to provide a single value that applies to all concrete mixes and all scenarios. ACI guidelines state that the acid-soluble chloride content most typically used in the United States ranges from 1.0 to 1.5 lbs/yd³ (1). Given the lack of an industry standard and the large number of variables which can affect the threshold value, it is important to evaluate instances of corrosion on an individual basis and treat them accordingly.

Fresh concrete is highly alkaline, with a pH of 12 or higher depending on the mix design used. Over time, due to environmental factors such as carbonation, the pH of the concrete begins to drop towards neutral. When the pH of the concrete reduces to below 10 corrosion of the reinforcing steel can be initiated.

A pH of less than 10 or a chloride concentration above the corrosion threshold leads to corrosion of the reinforcing steel due to a breakdown of what is referred to as the passivation layer on the reinforcing steel. When fresh concrete is placed, the high alkalinity causes a thin film of iron-oxide (Fe₃O₄) to form on the surface of the steel. This oxide layer protects the steel from reacting with any chlorides that may be present, provided the chloride concentration is below the corrosion threshold.

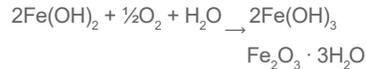
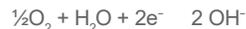
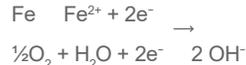
As concrete is exposed to chlorides and the concentration exceeds the threshold amount, the passivation layer begins to break down. The iron atoms that comprise the iron-oxide passivation layer begin to break free and react with the chlorides, shown in the chemical reaction below.



The iron that had previously been in a stable bond with oxygen at the passivation layer has been oxidized, and reacts with the negatively charged chloride ions to form iron dichloride. The iron has at this point freed itself of two electrons, which are free to react with oxygen and water. This is the first electrochemical reaction in the chloride induced corrosion process. Once the passivation layer has been breached, the iron atoms in the reinforcing steel will readily react with chlorides so long as they are present.

The reaction of the iron ions with chlorides initiates a series of electrochemical reactions in the presence of water and oxygen that comprise the corrosion process. We will briefly discuss each of the reactions however it is recommended you refer to one of the reference texts listed at the end of this manual for a deeper understanding of the process.

The complete electrochemical reaction process of chloride induced corrosion is shown below (6).



The first step in the process is the decomposition of the passivation layer, represented by the first reaction $\text{Fe}^{2+} + 2\text{Cl}^- \rightarrow \text{FeCl}_2$. The second reaction, $\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$, is the oxidation of the iron, or the loss of two electrons as discussed previously. The reaction $\frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2\text{e}^- \rightarrow 2\text{OH}^-$ represents the reduction of water and oxygen to form hydroxide ions. This is characterized by the gain of the two electrons which were freed during oxidation of the iron. This oxidation reduction process as defined by these reactions is responsible for the corrosion of steel.

The final two reactions relate to the formation of rust as a product of the corroded iron. The iron and hydroxide ions that are products of the two previous reactions react with one another in the fourth reaction, $\text{Fe}^{2+} + 2\text{OH}^- \rightarrow \text{Fe(OH)}_2$, resulting in the formation of an iron oxide, Fe(OH)_2 . In the presence of oxygen and water, this iron oxide reacts again to form a different iron oxide, $\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$, otherwise known as rust.

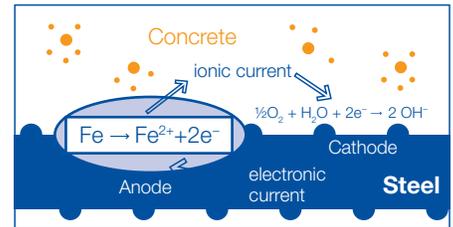


Figure 5 – Electrochemical Corrosion Reactions (16)

There are several important takeaways from this series of electrochemical reactions, with perhaps the most important being that there is no net consumption of chloride ions. Despite initially reacting with iron ions, the chlorides are left as a product following formation of iron hydroxide. This is extremely important as once the chlorides are present they will continue to be available to react with the steel and maintain the electrochemical corrosion process. There are methods such as chloride extraction that can remove the chlorides from concrete, but once corrosion has initiated it is generally accepted that the process can never be completely stopped.

Also of note is the production of hydrogen ions as a product of the reactions. Increased hydrogen concentration causes further deterioration of the passivation layer. The drop in pH along with the presence of chlorides leads to increased corrosion rates.

Because these are chemical reactions, temperature also plays a key role in the process. Elevated temperatures cause the reactions to occur more rapidly. The general rule of thumb for chemical reactions is that the rate of reaction will double for every 20 degree F increase in temperature. Thus we can expect chloride induced corrosion to be more active in the warmer months of summer and reduced or completely inactive during the winter.

Lastly, the reinforcing steel serves as both the cathode and anode of the corrosion cell. This means that while one area of the steel is corroding, an area immediately adjacent to it will not form rust.

Causes of Corrosion in Concrete, continued

Carbonation

Carbonation is also a chemical reaction that occurs in reinforced concrete, but unlike chloride induced corrosion it occurs due to elements that are an integral component of concrete. The cement paste that is the essential binder of Portland cement concrete contains several different sources of calcium. These include calcium hydroxide, Ca(OH)_2 , and calcium silicate hydrate, CSH. The calcium components of the cement paste react with carbon dioxide, CO_2 , to create calcium carbonate.

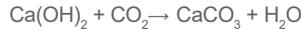
Carbonation itself does not lead to the formation of iron oxide however it does accelerate the initiation of corrosion by reducing the pH of the concrete and allowing the passivation layer to dissipate. Fully carbonated cement paste has a pH of approximately 8.4, well below the pH of 10, which is the limit for preservation of the passivation layer. Because carbonation reduces the pH, it can allow corrosion to initiate even when there is a very low concentration of chloride ions.



Figure 6 – Phenolphthalein Test of Carbonated Concrete (19)

Figure 6 above shows a piece of concrete being tested with phenolphthalein solution. Phenolphthalein is a pH indicator that is usually dissolved in alcohol containing some water. This simple test is often done to determine the level of carbonation occurring in a sample of concrete. As pH levels approach 10, the phenolphthalein solution begins to exhibit a dark pink color. As the pH drops below 10 there is no visible effect following application of the phenolphthalein solution. It can be seen in the figure that both the top and bottom of the sample are showing no visible reaction to the phenolphthalein solution. This indicates that carbonation is occurring and the pH has been reduced. The areas of the sample above that are showing a dark pink reaction indicate that carbonation has not affected the concrete and the pH remains high. Pink colors indicate healthy concrete when performing this test. Phenolphthalein indicator solution can be obtained from most testing laboratories.

One of the greatest difficulties with carbonation is that it begins almost immediately after placement of the concrete. Carbon dioxide in the air begins to react with the calcium components of the cement paste within a day or two of placement. This process is shown in the reaction below for calcium hydroxide:



The reactions work from the exterior of the concrete to the inside, eventually reaching the location of the reinforcing steel. Several factors can affect the rate at which carbonation occurs including the concrete density, porosity, carbon dioxide concentration, and humidity. Very dense concretes will not permit as much air and water to penetrate from the exterior. This serves to slow down the carbonation reaction. Very porous concretes will have the opposite effect due to the ease of entry for air and water. Similarly, cracks in the concrete will accelerate carbonation.

Humidity and moisture play a key role in trying to control carbonation. Water must be present in order for carbonation to occur. This is not a consideration in fresh concrete, but as the concrete ages and dries it becomes quite important. In order for the carbon dioxide to react with the calcium hydroxide as shown above, it must first dissolve in water to form hydrogen carbonate (carbonic acid, carbonated water), H_2CO_3 . From its dissolved state the carbon dioxide can then react with calcium molecules. If the concrete is too dry, this dissolution does not occur and carbonation is unable to occur. Conversely, if the concrete is too wet the carbon dioxide isn't able to penetrate the concrete, and carbonation is unable to occur. The limits for relative humidity of the concrete are considered to be 40%–90%. Outside of this range carbonation does not occur at an appreciable rate.

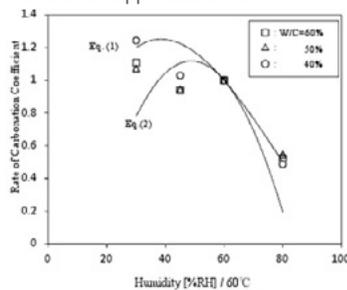


Figure 7 – Rate of Carbonation of Concrete for Different Water-Cement Ratios vs. Relative Humidity (11)

When fully saturated concrete or concrete exposed to a relative humidity of greater than 90% is not feasible, the preferred method of limiting carbonation is to maintain dry conditions within the concrete.

Chemical Attack

Though not a common occurrence, chemical attack on concrete can have severe consequences. One of the more common chemicals that concrete gets exposed to is sulfate, particularly in water treatment plants. Sulfate attack on concrete structures is a chemical attack that can lead to rapid deterioration of the concrete. Similar to carbonation, sulfate attack itself does not promote the development of iron oxide, or rust, on the reinforcing steel, however its effects promote conditions which expose the concrete to increased risk of chloride induced corrosion.

Sulfates can be supplied to concrete by both external and internal sources, though the former is far more common. Sulfates from external sources most typically enter through groundwater that has been contaminated with sulfate. This contamination can be caused by several factors including the oxidation of sulfate minerals in clay soils, acid-rain, and bacterial development in sewers which result in the formation of sulfuric acid. When these contaminants are present, the sulfates will generally dissolve in the ground water and penetrate the concrete as the water is absorbed into the pore structure. Seawater also contains sulfates, and marine structures are at risk via the same transport method.

Though it is rare for sulfate concentrations greater than 5% by weight to be introduced through internal sources it does occur from time to time. The sulfate would have been included in the concrete when it was mixed, likely due to either aggregate that has a high sulfate concentration or the use of excess gypsum in the cement mix. Both of these possible sources of contamination are easily controlled via adequate testing and certification of the aggregate being used as well as following industry standards for use of supplementary materials in concrete mix designs.

Whatever the source of sulfates in concrete, they lead to premature deterioration of the concrete. This can include cracks and spalls which provide easier access for both chlorides and carbon dioxide and thereby increase the possibility of or accelerate corrosion. Internal sources should be avoidable in most cases, and preventative measures which will be discussed on the following pages can be taken to slow or prevent the ingress of external sources of sulfate.

Effects of Corrosion in Concrete

Cracking and Spalling

The most visible effect of corrosion of reinforcing steel in concrete is the cracking and spalling of the host concrete. As the iron atoms chemically react and convert to iron oxide (rust) a dramatic expansive reaction occurs. The volume occupied by rust is in the range of four to ten times larger than the iron from which it was produced. This increased volume develops internal pressures in the concrete, which result in the development of tensile forces within the concrete. When these tensile forces exceed the strength of the concrete, the member will crack or spall in order to relieve the strain that had been developing. Once the concrete cracks it becomes susceptible to accelerated corrosion, further compounding the issue.

Reduced Structural Integrity

As steel reinforcement corrodes the iron is converted into rust. The issue of cracking and spalling is only half the problem with the development of rust however. As the iron oxide develops it begins to flake off from the steel reinforcement, resulting in a reduction in the cross-sectional area of the reinforcing bar. Losses in cross-sectional area of reinforcing bars directly relate to a decrease in strength capacity for the structure. As corrosion continues, the loss of cross-sectional area will become more pronounced, and in extreme cases could lead to a catastrophic failure of the structural system. Thus it is imperative to address corrosion both before it begins as well as after initiation to preserve the structure as best as possible and achieve maximum life expectancy and public safety.

Aesthetics

While not a concern from a strength or safety standpoint, corrosion can create unsightly structures that may lead to public perception that the structure is in an unsafe condition. As the reinforcing steel rusts, it is quite common for rust stains to appear in the concrete, particularly where cracks have propagated. The result is red and orange stains on the structure which match the color of rusting steel. In addition to the stains, the appearance of excessive cracks and spalls leads to the perception that the structure is deficient regardless of the actual capacity. This can be of particular concern in parking and other structures where the concrete is often visible to the public.

Corrosion Mitigation Strategies

The problem of corrosion is a complex and multi-faceted issue, and proper mitigation of corrosion is no different. The best approach to controlling corrosion of concrete structures often involves a system of solutions which work together to control the various parameters that feed the corrosion process. Making things more difficult is that different solutions are often required depending on the rate of corrosion, age of the structure, type of repairs, and other variables.

In order to simplify the selection process, it is useful to break down corrosion control strategies into three categories. Each category is built around the objectives of the different strategies. These categories include corrosion prevention, corrosion protection, and corrosion mitigation.

Corrosion Prevention

The objective of a corrosion prevention strategy is to stop corrosion before it begins. Due to the aggressiveness of corrosion, prevention typically deals with new structures; however there could be cases where existing structures have not started to corrode and preventative measures are required. Regardless of the age of the structure, in order to prevent corrosion from occurring it is necessary to remove some or all of the components required to initiate the electrochemical reactions.

We have previously discussed the various causes of corrosion, and pointed out that for any of the three main causes to occur water must be present within the concrete. Thus if we are able to keep the concrete dry, the electrochemical process will not initiate. Dry concrete is at the heart of a corrosion prevention strategy.

The best approach to maintaining dry concrete is to use a water repellant sealer on the surface of the concrete. A common sealer is the liquid, surface applied variety which are typically either silane based or solvent based. Many technologies utilize a combination of silane and solvent to achieve water repellency. Membrane systems may also be used as sealers. A common water repellant membrane for slabs and decks include polyurethane deck coatings such as the Master Builders Solutions MasterSeal Traffic 1500 and MasterSeal Traffic 2500 systems. Sheet membranes are another type of sealer that is often used, particularly for below-grade applications. These membrane sheets may be self adhering or require additional adhesive, and also may be inherently water repellant or activate upon contact with moisture and pressure to provide hydrophobic properties.

Regardless of the technology used, an effective sealer prevents water from penetrating into the concrete. In addition to maintaining dry concrete, the sealer also keeps any external chloride sources from penetrating into the concrete. The chlorides remain on the surface of the concrete where they are carried away as water soluble salts. By maintaining a chloride-free environment the sealer assists in maintaining the passivation layer on the reinforcing steel, and can serve a vital function in a corrosion prevention strategy.

It is important to keep in mind that sealers do not last forever, making routine maintenance a key component of any corrosion prevention strategy. In addition to the need to periodically reapply the sealer, cracks often form in concrete for several reasons exclusive of corrosion damage. Routine inspection of the structure and repair of any cracks or spalls that do appear is imperative to maintaining a dry concrete substrate.

The effects of corrosion often lead to extensive repairs at considerable expense to building and infrastructure owners. The use of a sealer on concrete that has not yet started to corrode will go a long way to preserving the lifespan of the concrete and delaying the onset of costly repairs. The material and installation costs associated with sealers are very low when compared to the potential costs of corrosion damage. See the following section for details on the water repellents offered by Master Builders Solutions.



Figure 8 – Corrosion Induced Failure Following Application of a Deck Membrane

Corrosion Mitigation Strategies, continued

Sealers are very effective at preventing corrosion; however it is important to reiterate that once corrosion has been initiated it will continue on its own due to the fact that there is no net consumption of the chlorides. While the use of a sealer on an actively corroding structure will help to prevent additional chlorides from penetrating into the concrete, it will not completely solve the corrosion problem on its own. This is an important consideration when making repairs. Consider for example an oceanfront balcony undergoing severe corrosion which has led to cracks and spalls, ripping the carpet used to cover the balcony. If the corrective action taken is only to repair the damaged concrete and install a sealer to keep moisture out of the slab, the same repairs will likely be required in the very near future as nothing has been done to address the active corrosion. Sealers will help keep out new moisture and chlorides, and over time may allow the concrete to completely dry, however the presence of any moisture in an actively corroding environment will maintain the electrochemical process. It is always recommended to use supplemental corrosion control methods in addition to sealers in the case of actively corroding reinforced concrete.

There are also other options available as part of a corrosion prevention strategy beyond sealers. Alternative reinforcing that does not corrode such as FRP bars can be installed in lieu of traditional reinforcing. Stainless steel reinforcing steel provides much higher corrosion resistance than typical iron bars and is often used to delay the onset of corrosion. Reinforcing steel can also be coated with epoxy prior to installation to act as a sealer however care must be taken with this approach not to damage any of the epoxy coating. As is always the case, all options should be considered for an individual project in order to provide the highest level of corrosion prevention to the structure.

Corrosion Protection

When corrosion of reinforcing steel is detected at an early stage, measures can be taken to stop the spread of corrosion to other areas of the concrete structure. We refer to this strategy as corrosion protection. The objective here is to stop or slow down the existing corrosion as well as prevent additional corrosion in other parts of the structure.

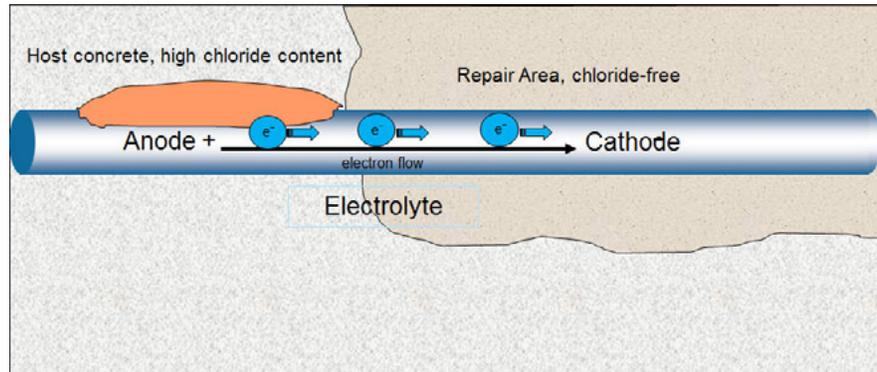


Figure 9 – Incipient Anode Effect at Concrete Patches

We now know that the corrosion cell consists of both a cathode and an anode, with the active corrosion occurring at the anode portion of the corrosion cell. This results in localized corrosion of the reinforcing steel at the anode, with the cathode remaining clean and in its original state. The effects of this often result in localized corrosion in a structure in the early stages of corrosion in a concrete structure.

The typical course of action to address localized corrosion is to complete concrete repairs at the effected areas. The repair should include removal of all of the unsound concrete in the repair area. Additionally, the reinforcing steel that passes through the repair area should be cleaned with a wire brush such that any rust on the surface has been completely removed. Once the repair area has been adequately cleaned, the concrete repair should be completed following the published installation recommendations for the Master Builders Solutions repair mortar that has been selected

Localized repairs of this type require special considerations pertaining to the future protection of the concrete structure. Because corrosion had been initiated, we know that the concrete contains sufficient chlorides to have initiated corrosion or that the pH has dropped below 10. In either case the passivation layer on the steel has been breached, and corrosion can initiate in the existing concrete. Within the repair area, however, a new, nearly chloride-free patching material has been installed which will also have a high pH upon initial placement. This creates a phenomenon referred to as the ring anode effect, the halo effect, or the incipient anode effect.

INCIPIENT ANODE EFFECT

The incipient anode effect refers to the reversal of the cathode and anode at an existing corrosion cell. When the concrete repair is made, we have created a nearly chloride-free, high pH area of the slab immediately adjacent to a chloride-contaminated, lower pH area of the slab. The existing area of the slab surrounding the patch had previously served as the cathode and was not corroding. However this part of the steel that was previously the cathode now has a much higher potential than the concrete patch. It also has either sufficient chlorides or low enough pH to initiate corrosion, or both. The resulting effect is that the existing cathode now becomes anodic, and the patch area becomes cathodic. In simpler terms, we have reversed the corrosion cell such that corrosion will now occur in the steel immediately outside of the patch area.

Figure 9 above depicts the formation of the incipient anode effect. The dark area on the upper right hand side represents a recently placed concrete repair with minimal chloride concentration. The lighter area surrounding the repair area has a higher chloride concentration and likely lower pH than the repair mortar. This creates a difference in potential between the repair and existing concrete. The potential difference along with higher chloride concentrations and variance in pH leads to accelerated corrosion of the reinforcing steel in the existing concrete immediately adjacent to the repair.

It is very common to see concrete structures that have a succession of repairs adjacent to one another, and these are typically due to the incipient anode effect. When a patch repair is made and no consideration is made to the surrounding concrete, accelerated corrosion occurs in areas of the existing concrete adjacent to the patch. Often repairs of the existing adjacent areas will be required in as little as one year after the original repair due to the accelerated corrosion. If the incipient anode effect is not addressed in the second repair the problem will occur once again. This process will continue to repeat itself over and over unless adequate steps are taken to prevent its spread. The results of the incipient anode effect are often referred to as chasing the repair, as continued ignorance to the problem will ultimately result in the entire member being repaired.



Figure 10 – Incipient Anode Effect on Parking Structure

Clearly it is critical to the success of corrosion protection strategies to consider the effects of the incipient anode effect. Equally important to the successful implementation is the use of high quality repair materials that have been installed according to ICRI repair guidelines and the individual product recommendations provided by Master Builders Solutions.

Corrosion protection is intended to address minor and localized corrosion problems on a concrete structure. It can be a highly effective tool to accomplish this objective when proper materials are used and properly installed. This type of corrosion strategy is not recommended for widespread corrosion problems due to the difficulty associated with cleaning the steel of a structure in its entirety.

Corrosion Mitigation

If corrosion is left unchecked, or is particularly aggressive, it is very likely that a concrete structure will experience widespread damage and deterioration of its reinforcing steel. In these situations, performing localized repairs at each of the damaged locations is generally not feasible due to the quantity of repairs required.

When situations arise where widespread reduction of corrosion is required, the best course of action is to implement a corrosion mitigation strategy. Corrosion mitigation is intended to reduce active corrosion across the entire structure as opposed to a small localized area. This is the key differentiator between mitigation and protection. When corrosion mitigation is required it is probable that the majority of the structure is exhibiting the effects of corrosion. A comprehensive solution is required to keep the corrosion in check and preserve the life of the structure.

Corrosion mitigation is typically achieved through the use of surface applied corrosion inhibitors or impressed current cathodic protection (ICCP) systems. Both of these solutions are usually applied to the entire structure, although localized applications are possible. The objective of these technologies is to prevent additional deterioration of the reinforcing steel and slow the active corrosion rate such that the life of the structure can be extended as long as possible.

There are many corrosion mitigation products in the marketplace which have demonstrated varying degrees of success. When choosing a product for this type of application it is very important to research the technology and request independent testing to show that the product will successfully reduce corrosion in the structure. Many of the products will only function if they penetrate to the depth of the steel, while others such as Master Builders Solutions MasterProtect 8000 CI also react with the concrete to provide additional levels of corrosion protection.

Successful implementation of a corrosion mitigation strategy should include maintenance and monitoring plans. When corrosion has reached the point that this level of protection is required, it is likely critical to the performance of the structure that corrosion is drastically slowed down. Continued monitoring and testing ensures that the owner is getting the results they desire and that corrosion is in fact being reduced. Monitoring may be achieved via embedded probes or external methods such as linear polarization and half-cell measurements.

The structural integrity of the concrete structure should always be considered, particularly when severe corrosion is identified. The corrosion strategies that have been discussed will slow and/or reduce corrosion, but they do not restore lost capacity. Severely corroded structures should always be evaluated by a professional engineer to ensure that adequate load capacity remains despite the loss of cross-sectional area in the reinforcing steel. Should there be a concern with structural capacity the use of additional reinforcing steel, steel plates, or FRP strengthening systems is warranted.

Corrosion Solutions

The following section provides information about the various corrosion solutions available from Master Builders Solutions. The list of systems is not all inclusive, and where additional systems exist they have been noted. When working with these products in the field it is essential to follow all safety instructions and wear appropriate personal protective equipment at all times. Material Safety Data Sheets for all of the products shown are available at master-builders-solutions.com/EN-US and should be reviewed thoroughly prior to handling any of the products.

MasterProtect® H 1000

MasterProtect H 1000 is a clear, breathable, 100% silane water repellent sealer that can be used for corrosion prevention or as part of a corrosion protection and/or mitigation strategy. MasterProtect H 1000 will penetrate deep into the substrate, sealing out water, chloride ions, and acids. It does not harm adjacent metal, glass, wood, or painted surfaces, all of which do not require cleaning after application. This 100% silane repellent offers high-performance water repellency while allowing any accumulated moisture in the host concrete to evaporate out without damaging the sealer. Breathability is an essential property of any sealer used to prevent corrosion, particularly when using on fresh concrete which still retains much of its mix water.

APPLICATIONS

MasterProtect H 1000 is suitable for use on both horizontal and vertical concrete surfaces. These surfaces can be new or existing, but when using on fresh concrete it is important to ensure that the concrete has reached 80% of its design strength. This typically occurs between 14 and 28 days after initial concrete placement but varies with mix design and temperature. MasterProtect H 1000 is designed to be used on above grade applications only, however it can be used on both interior and exterior applications including traffic bearing concrete substrates. Typical structures where MasterProtect H 1000 is used include bridge decks and substructures, concrete highway surfaces, ramps and barrier rails, parking garages, stadiums, cooling towers, and other reinforced concrete structures.

PACKAGING AND COVERAGE

MasterProtect H 1000 is packaged in both 5 gallon pails and 55 gallon drums, both of which have a 2 year shelf life when properly stored. The typical coverage rate for the material is in the range of 250–400 ft²/gallon. The actual rate on a specific project depends largely on the porosity of the substrate. Extremely porous substrates may require two coats in order to achieve adequate coverage.

When using any sealer it is recommended to apply a small 5 ft by 5 ft test area prior to starting the job. This will allow verification of the coverage rate required of the substrate and ensures that the desired results are being achieved. Allow 5–7 days for the sealer to fully react before evaluating the installed properties.

INSTALLATION REQUIREMENTS SURFACE PREPARATION

Proper surface preparation is essential to the successful installation of a surface penetrating sealer. Prior to application, substrates must be clean of all sand, surface dust and dirt, oil, grease, chemical films and coatings and other contaminants. The surface should also be profiled (typically by abrasive blasting or high pressure water blasting). If water blasting is used to profile the substrate it is essential to allow a minimum of 72 hours drying time prior to application of MasterProtect H 1000.

APPLICATION

The application method used on a project varies with project requirements, type of application, and accessibility. For horizontal surfaces, MasterProtect H 1000 is typically applied by flooding action. The sealer may also be applied with low-pressure spray or roller followed by brooming for even distribution on a horizontal surface. On vertical surfaces the MasterProtect H 1000 may be applied with a low-pressure non-atomizing sprayer starting at the bottom and working upward to achieve even distribution.

Crack injection, patching, and joint sealants can be installed before or after application of the sealer.

There are some environmental considerations that must be taken into account when installing MasterProtect H 1000 as well. Air, material, and surface temperatures should be 40° F or higher during application. If the temperature is expected to fall below 20° F within 12 hours do not apply the sealer as this will adversely affect the reaction of the sealer with the concrete and lead to poor performance. It is also important that the sealer not be applied when rain is expected within 4 hours following application. Hydrozo100 is still able to react with the rainwater during this timeframe which alters the chemistry of the product and reduces performance.

DRYING TIME

The time required for MasterProtect H 1000 to dry depends on environmental conditions, but at a temperature of 70° F and 50% relative humidity it will typically dry in 4 hours. Cooler temperatures or higher relative humidity can extend the drying time. If environmental conditions exist that could potentially extend the drying time it is important to also consider the weather. The surface must be free of rainwater until the material is dry, so extended drying times also require extended periods of dry weather.

CLEANUP

If any tools or equipment are used during the installation of MasterProtect H 1000 they can be cleaned with mineral spirits or Xylene.

SIMILAR MASTER BUILDERS SOLUTIONS SEALERS

The following products comprise the complete list of surface applied sealers in the Master Builders Solutions product offering. For additional information regarding these products, refer to the product datasheets available at www.master-builders-solutions.com/EN-US

- MasterProtect H 1001—MasterProtect H 1000 with an oliophobic additive for stain resistance
- MasterProtect H 440 HZ—solvent based 40% alkylalkoxysilane
- MasterProtect H 440 VT—solvent based 40% silane
- MasterProtect H 200—water based 20% alkylalkoxysilane
- MasterProtect H 400—water based 40% alkylalkoxysilane
- MasterProtect H 107—water based silane/siloxane sealer

MasterProtect P 8100 AP

MasterProtect P 8100 AP is a one-component, zinc-rich epoxy primer designed to prime and protect reinforcing steel from corrosion. The primer prevents corrosion via electrochemical means to prevent development of the incipient anode effect. The zinc component in the primer creates a galvanic corrosion cell with the steel in which the zinc will corrode preferentially to the steel, delaying the onset of corrosion of the reinforcing steel. The corrosion protection offered by MasterProtect P 8100 AP makes it ideal for use in a corrosion protection or prevention strategy.

The epoxy chemistry utilized in MasterProtect P 8100 AP makes it compatible with all repair mortars sold by Master Builders Solutions. It does not have a restrictive pot life which allows ample time for proper application and reduces material waste. MasterProtect P 8100 AP is also very easy to work with as it is a single component product that does not require mixing in the field.

APPLICATIONS

MasterProtect P 8100 AP is most commonly used in shallow repairs that do not provide enough clearance for the use of more robust corrosion protection systems such as galvanic anodes.

PACKAGING AND COVERAGE

The MasterProtect P 8100 AP is packaged in 1 quart cans with a yield of 150–250 lineal feet per quart. This coverage rate is based on use with #4 reinforcing bar. The coverage rate will decrease as the bar diameter of the reinforcing steel increases due to the increase surface area associated with larger bars. The shelf life of the product when properly stored is one year.

INSTALLATION REQUIREMENTS

SURFACE PREPARATION

When applying MasterProtect P 8100 AP it is important that all reinforcing steel is fully exposed. Any corroded steel must be fully exposed by chipping out the concrete surrounding the corroded steel. All loose scale and corrosion deposits must be removed, and particular attention should be paid to the backside of the exposed steel bars. Once fully exposed, the steel should be mechanically abraded to remove corrosion from pits and any surface imperfections. If during the cleaning process it is observed that significant losses in cross-sectional area have occurred it may be necessary to replace the existing reinforcing steel or add supplemental strength using alternative methods such as FRP strengthening as determined by the project engineer.

APPLICATION

MasterProtect P 8100 AP must be stirred thoroughly in the can prior to use. The stirred material should be applied to the dry reinforcing steel as soon as possible following completion of the preparation work, but not more than 3 hours afterward. One full and unbroken coat is first applied at 4 mils wet film thickness using a suitable brush. Take care to ensure that the back of the exposed steel reinforcing bars are properly coated. After the first coat dries, a second coat should be applied at 4 mils wet film thickness to ensure complete coverage of the steel. Any localized areas that are not covered can serve as a corrosion hotspot and lead to accelerated corrosion.

Concrete repair materials can be applied once the MasterProtect P 8100 AP is fully dry. The coated reinforcing steel should not remain exposed to the elements for longer than 7 days before overcoating or applying repair materials.

DRYING TIME

MasterProtect P 8100 AP dries to the touch in 20 minutes to 1 hour depending on the application thickness and environmental conditions.

CLEANUP

If any of the MasterProtect P 8100 AP comes into contact with hands or skin clean the affected area immediately with soap and water or industrial hand cleaner. Never use a solvent for cleaning the product off skin.

Removal of MasterProtect P 8100 AP from tools and equipment can be achieved using a solvent such as Xylene or MEK immediately after use.

MasterProtect Anodes

MasterProtect Anodes are galvanic anodes comprised of zinc plates encased in a proprietary mortar with wire ties. The anodes are used as part of a corrosion protection strategy, most commonly when completing patch repairs where the incipient anode effect is probable. Galvanic anodes have been used extensively in concrete repairs for many years however MasterProtect Anodes represent a significant improvement over existing technologies.

Galvanic anodes function by electrical connection to the reinforcing steel via steel tie wires. The wires are tied to the reinforcing steel to allow a current to pass between the anode and the reinforcing steel, redirecting the corrosion process to the anode and preventing corrosion of the reinforcing steel. Zinc is less noble than iron, which is to say it is more anodic than iron. In simpler terms this means that zinc corrodes preferentially to iron. Thus by connecting zinc plates to the reinforcing steel the corrosion reactions are redirected to the zinc plate within the anode, protecting the reinforcing steel from continued corrosion.



Figure 11 – MasterProtect Anode in Salt Water Solution

The MasterProtect Anode is connected to the top reinforcing steel bar which is showing no signs of corrosion. The bottom steel reinforcing bar is not connected to the anode and is undergoing corrosion as can be seen by the rust formation on the left end of the reinforcing steel bar.

Improvements to the zinc used in the MasterProtect Anodes are one of the many benefits offered over existing technologies. The zinc used in the MasterProtect Anodes is ASTM B418 Type II Zinc. ASTM B418 Type II Zinc has strict limitations on the presence of other types of metals, making it more pure than Type I zinc. The higher purity of the Type II zinc minimizes the risk of auto-corrosion and extends the life of the anode.

Corrosion Solutions, continued

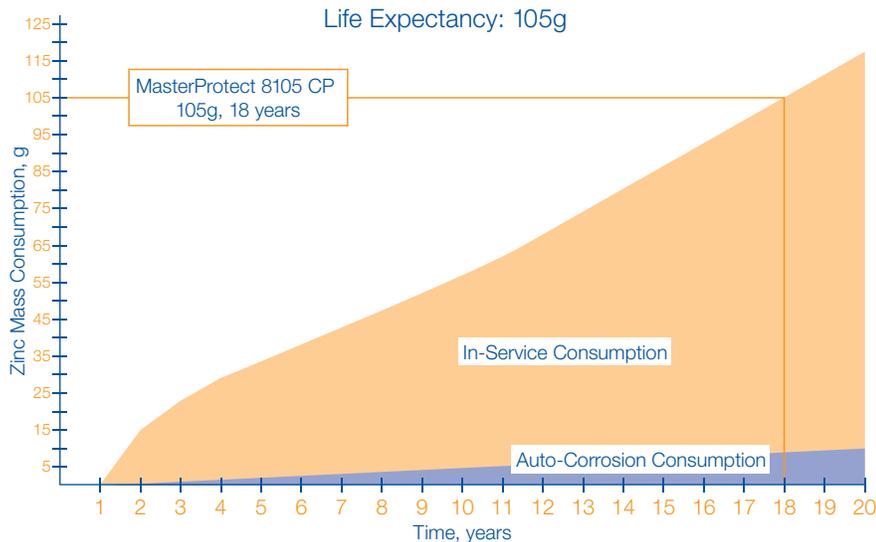


Figure 12 – Auto-Corrosion of 105g Anode and Related Reduction in Life Expectancy

By limiting the amount of dissimilar metals, particularly iron, contained in the zinc plates within MasterProtect Anodes, the potential for premature corrosion of the zinc is minimized. Auto-corrosion impacts the service life of an anode. The zinc plates in the anodes are of finite mass. Once all of the zinc has corroded the anode is no longer able to provide protection to the reinforcing steel. By utilizing Type II zinc, the Master-Protect Anodes provide the maximum service life possible for the zinc encased within.



Figure 13 – Type II Zinc Plates MasterProtect Anodes

Another improvement related to the zinc contained within the MasterProtect Anodes is a dramatically increased surface area. Older anodes typically used a solid zinc cylinder. The increased surface area of the Master-Protect Anodes allows for more evenly distributed corrosion of the zinc plates, increasing its efficiency and extending the service life of the anode. It also allows for the corrosion by-products to move away from the zinc plate into the encasement mortar more easily, which also increases the efficiency of the anode.

Increased surface area also allows for less restricted movement of the ionic path of the corrosion cell which in turn increases the efficiency of ionic transport.

The encasement mortar is equally important to the success of a galvanic anode, and the mortar used with the MasterProtect Anodes utilizes a dramatic improvement over existing technologies. The MasterProtect Anodes use the process of chelation to maintain function of the anode. ASTM A 380 defines chelates as chemicals that form soluble, complex molecules with certain metal ions, inactivating the ions in solution so they cannot normally react with another element or ions to produce precipitates or scale (ASTM A 380). The chelating agent in the MasterProtect Anodes bonds with the zinc ions that corrode off the surface of the plates. The molecule formed cannot react at the surface of the zinc plate which prevents the formation of precipitate. By keeping the surface of the zinc plates clean of precipitate, the chelating agent acts to prevent passivation of the zinc plates. Passivated zinc plates will not corrode, thereby shutting down the anode and rendering it ineffective.

A key advantage of the chelation process is that it has been found to be relatively independent of the pH of the mortar. Independent third-party testing performed on the MasterProtect Anodes showed superior performance at a pH less than 9.0. This same testing showed that high pH is not maintained over time within the encasement mortars, which can result in re-passivation of the zinc in systems that require a high pH.

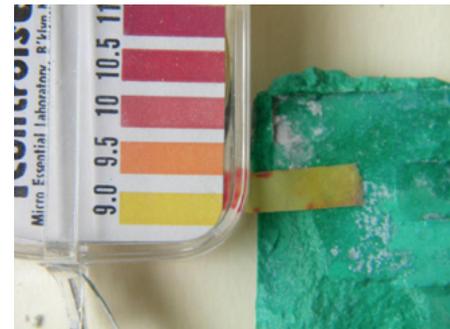


Figure 14 – pH of MasterProtect Anode Mortar After 6 Months (11)

MasterProtect Anodes come in three sizes, a green 65 gram anode, a blue 105 gram anode, and an orange 150 gram anode, all of which incorporate galvanized steel, pre-twisted tie wires to ensure proper standoff. The grams represent the mass of zinc contained in the anode. MasterProtect Anodes are color coded to allow for easy inspection in the field to ensure the correct size is used. It is important to note that the additional mass in the anodes does not affect the required spacing of the anode. The increased mass simply extends the service life of the anode. It will take longer to fully consume 105 grams of zinc than 65 grams.

Several installation details for the MasterProtect Anodes are available on the Master Builders Solutions website and are also included in the appendix of this manual. These include details of minimum cover and edge distance, use of the anodes with high resistivity repair mortars, typical installation, and spacing requirements. The required spacing is related to the steel density ratio in the concrete. With a greater volume of steel in the repair area the anodes must be spaced closer together to adequately protect all of the reinforcing steel. This is related to what is referred to as the 'throwing capacity' of the MasterProtect Anodes. The throwing capacity relates to how far down the reinforcing steel the anode is able to distribute current and thereby provide protection to the reinforcing steel. When more steel is present in a unit area of concrete the reach of the anode is diminished, and the spacing must be tightened up to provide adequate protection.

The MasterProtect Anodes have undergone extensive independent, third-party testing to demonstrate the improved performance of the new technology. This testing evaluated the service life of each of the three anodes, pH of the encapsulation mortar, anode/cathode resistance, polarization/depolarization, and potential shift. The study demonstrated superior performance of the MasterProtect Anodes and may be reviewed by contacting your local Master Builders Solutions sales professional.

APPLICATIONS

MasterProtect Anodes are used in the repair of reinforced concrete structures as a protective measure against development of the incipient anode effect. They should be used when patching concrete substrates containing chlorides or wherever corrosion of the reinforcing steel is possible. MasterProtect Anodes are suitable for use in post-tensioned, prestressed, or conventionally reinforced structures. The anodes do require an electrical connection however, so care must be taken if the reinforcing steel is covered with an epoxy coating or a sheathing of some kind. The tie wires of the anode must be connected directly to the steel without any interference. MasterProtect Anodes can provide corrosion protection to both interior and exterior concrete and masonry structures.

PACKAGING AND COVERAGE

The packaging of the MasterProtect Anodes varies depending upon the size of the anode. The 65 gram anode is slightly thinner than the others due to the fact that it contains only one zinc plate, and comes in boxes of 30 anodes. The 105 gram and 150 gram anode both contain two zinc plates fastened together, making them slightly thicker, and are packaged in boxes of 24 anodes. All three sizes have a shelf life of 3 years when properly stored. As previously mentioned, the spacing requirement is determined by calculating the steel density in a unit area of the substrate, and coverage rate will vary accordingly. Determination of the required number and spacing of the MasterProtect Anodes must be determined and specified by the design professional.

INSTALLATION REQUIREMENTS

SURFACE PREPARATION

All loose and spalled concrete should be removed in accordance with conventional repair guidelines outlined by ICRI. The required cover and placement of the MasterProtect Anodes should be considered during the removal of existing concrete to ensure that all installation requirements are met.

APPLICATION

The MasterProtect Anodes will typically be installed around the perimeter of a concrete repair and on plane with the reinforcing steel. This ensures that proper cover is provided. Consult the installation details included in the appendix of this manual and also available on the Master Builders Solutions website for additional information regarding the required cover.

The anodes must be placed such that the entire anode and wire connections are encased in the concrete repair material.

The surface of the reinforcing steel should be untreated and cleaned to a near white surface condition in those areas where the MasterProtect Anodes will be electrically connected. No other pretreatment or post treatment of the steel is necessary or permitted.

Unlike older generations of anodes, the MasterProtect Anodes do not need to be pre-soaked and can be installed directly out of the box. A quality concrete repair following ICRI guidelines requires that the existing substrate be in a saturated surface dry condition prior to installing the repair material. After installing the anodes, the substrate can be wetted to achieve the SSD condition. This process will sufficiently wet the MasterProtect Anodes and no additional preparation is required.

In order to achieve the expected throwing capacity of the anodes, the MasterProtect Anodes must be installed with a 1" standoff. The integrated galvanized steel tie wires included with the anodes come pre-twisted to ensure the appropriate standoff is provided on every application. The tie wires should be securely fastened to the reinforcing steel by wrapping them around the reinforcing steel and twisting the tie wires together. Electrical connection to the reinforcing steel can be verified by checking for a DC resistance of less than 1 Ohm between the reinforcing steel and the anode connection wire.



Figure 15 – Integrated Standoffs on MasterProtect Anodes

SPECIAL CONSIDERATIONS

Because MasterProtect Anodes rely on an electrical connection with the reinforcing steel to function properly, it is essential to ensure continuity of the reinforcing steel. An anode will only provide protection to steel to which it has a direct electrical connection. The throwing capacity of the anode does not allow it to protect steel to which it is not electrically connected. Thus it is important to test for continuity of the steel within the repair area prior to installing the MasterProtect Anodes. If it is determined that there is a discontinuity in the steel, the effected bars can be tied together using wire ties or welding bonds. If it is not possible to create continuity it is essential to provide an additional MasterProtect Anodes to each bar that is not electrically connected to the other reinforcing steel.

Consideration must also be given to the repair material being used for the concrete repair. When MasterProtect Anodes are specified in a repair, the repair material selected should ideally have an electrical resistance of less than 20,000 Ohm-cm. Use of repair materials with resistance values greater than 20,000 Ohm-cm may limit the anodes from functioning properly, however they may still be used if a suitable embedment mortar is used to surround the anode, reinforcement to tie wire connection, and immediately adjacent concrete. The pre-pack mortar must have an electrical resistivity of less than 20,000 Ohm-cm and must fully encapsulate the MasterProtect Anode.

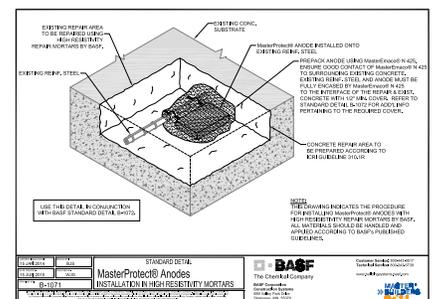


Figure 16 – Pre-Pack Mortar Detail

See Appendix for Full Page Detail

Master Builders Solutions repair mortars that have been tested for resistivity per FM 5-578 (7) that may be used without a pre-pack mortar include:

- MasterEmaco N 400
- MasterEmaco N 400 RS

Additional repair mortars have undergone resistivity testing and may also be used without a pre-pack mortar. Consult with a Master Builders Solutions representative for a complete list of available repair mortars.

Corrosion Solutions, continued

MasterProtect 8000 CI

MasterProtect 8000 CI is an organo-functional silane, surface applied corrosion inhibitor suitable for use as part of a corrosion prevention, protection, or inhibition strategy. It is a highly advanced amino-silane based inhibitor which combines the capabilities of silane molecules with an amine functional group to provide a mixed inhibitor effect. MasterProtect 8000 CI is a clear liquid which does not cause any change to the surface appearance of a concrete substrate. It can be used with most Master Builders Solutions Sealants and Coatings, and also will not act as a bond breaker in repair or overlay situations. MasterProtect 8000 CI is a penetrating residue-free which eliminates the need to re-clean the surface of the deck prior to installing Master Builders Solutions Sealants and Coatings, saving on time and reducing jobsite complexity.

Typical surface applied corrosion inhibitors require the inhibitor to penetrate the concrete to the depth of the reinforcing steel for there to be any effect. The functional group acts at the surface of the reinforcing steel to re-passivate the steel and reduce active and future corrosion. One of several issues with a strictly organic corrosion inhibitor is that it must reach the steel in order to function properly. If the amine group is unable to penetrate the concrete to the depth of the reinforcing steel no reactions occur and the steel is not re-passivated.

MasterProtect 8000 CI functions in a similar fashion to the organic inhibitors as far as its amine group is concerned, with the amine group re-passivating the reinforcing steel when it is able to penetrate to the depth of the steel. MasterProtect 8000 CI has a viscosity of less than 1 centipoise and a very low surface tension of less than 20 dynes/cm. This combines to make a very fluid material that is much more efficient at penetrating concrete than other technologies. The result is a much higher success rate in reaching the steel. However, in the rare case that MasterProtect 8000 CI is not able to penetrate to the steel, the presence of the silane molecules provides alternative means of corrosion inhibition.

The most observable property of MasterProtect 8000 CI is the water repellent sealer capabilities of the silane component. Previous sections discussed the use of sealers as a method for corrosion prevention by keeping moisture and chlorides from penetrating the concrete. The silane component of the MasterProtect 8000 CI provides this same benefit with the added feature of its ability to act as a corrosion inhibitor.

MasterProtect 8000 CI protects concrete from penetration of liquid water but is permeable to water vapor. Thus while keeping new moisture from penetrating into the concrete, MasterProtect 8000 CI will allow any moisture contained in the substrate to evaporate out. This can be of particular importance when used on fresh concrete.

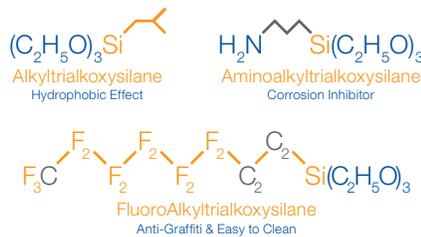


Figure 17 – Various Functional Groups of Silanes

What is typically less understood is the functionality of silane molecules in the presence of an amine functional group. Depending on the chemical reaction that takes place, silanes can be created with different functionalities. MasterProtect 8000 CI utilizes multiple silane functionalities to create different effects on the concrete substrate. These include the formation of a hydrophobic layer as well as a corrosion inhibition effect.

The creation of the hydrophobic properties begins when the silane hydrolyzes to form silanol and alcohol. Next the silanol group condenses, allowing for a bond with the hydroxides on the concrete surface to form. Figure 18 depicts the chemical reactions associated with this process. The R in the figure represents the hydrophobic portion of the compound. CH_3OH is the alcohol produced when the silane reacts with water, which is methanol in the case of MasterProtect 8000 CI. The substrate in this case is the pores in the concrete. This series of reactions leads to the creation of the hydrophobic layer observed on the surface of the concrete treated with MasterProtect 8000 CI.

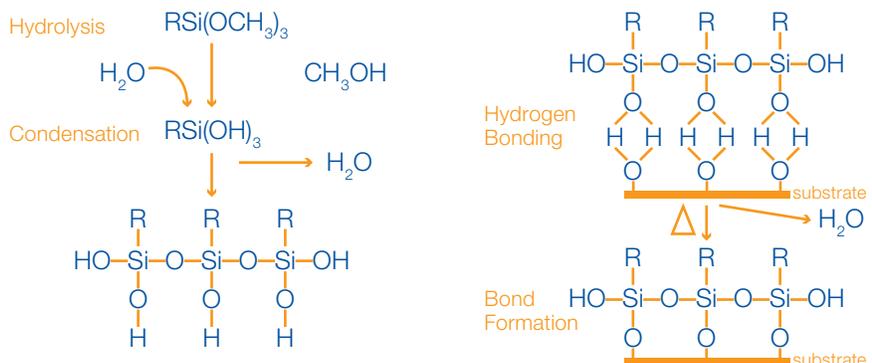


Figure 18 – Reaction of Alkylalkoxy Silane with Water (hydrolysis) to Produce Silanol and Alcohol Followed by Condensation and Bonding to the Pores of the Concrete Substrate (13)

Aminoalkyltrialkoxysilanes can react within the concrete to disrupt the conductivity of the electrolyte. The reaction increases the resistivity of the concrete immediately adjacent to the reinforcing steel which in turn slows down the electrochemical reactions that make up the corrosion process. The reduction in the rate of the electrochemical reactions leads to a reduced corrosion rate which is known as corrosion inhibition.

Independent testing of MasterProtect 8000 CI has shown it to be very effective at reducing active corrosion in steel reinforced concrete. The combination of the amine group working at the steel and the silane-concrete interaction serve to reduce active corrosion and prevent the onset of additional corrosion activity. The test results in Figure 19 on the next page demonstrate this effect on three concrete blocks versus an untreated control.

APPLICATIONS

MasterProtect 8000 CI can be used effectively on almost any type of steel reinforced concrete. Typical structures include parking decks, façades, balconies, walkways, piers, bridge decks, beams, and columns but other applications are available as well. It is also often used in marine environments with high relative humidity and airborne chlorides as well as areas subject to application of deicer salts.

MasterProtect 8000 CI can be placed on concrete that has adequately cured to 80% of its design compressive strength as part of a corrosion prevention strategy, and existing concrete as part of a corrosion protection or inhibitor strategy. While MasterProtect Anodes are very effective for patch repairs often times there are a large amount of repairs on a structure which may make it easier for the installer to apply MasterProtect 8000 CI over the entire surface. It can be applied in horizontal, vertical, and overhead applications following proper surface preparation, which makes it a very versatile material for use in corrosion mitigation strategies.

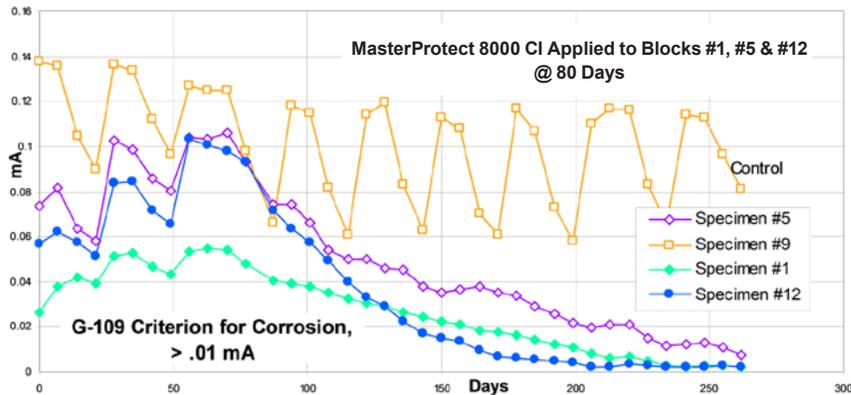


Figure 19 – Reduction of Corrosion Current Following Treatment with MasterProtect 8000 CI (10)

Previously corroding ASTM G109 specimens were dried and then cyclically ponded and dried until steady state corrosion activity was established. At the completion of the drying cycle at 80 days, specimen #9 received no treatment and served as a control while the other three specimens (#5, #1 and #12) received MasterProtect 8000 CI applied according to our instructions and allowed to dry for 7 days before salt water ponding was resumed at intervals indicated by the swings in the corrosion activity of the control specimen. The decrease in corrosion current began immediately and all three treated specimens eventually reduced the corrosion to acceptable levels according to the testing criteria.

PACKAGING AND COVERAGE

MasterProtect 8000 CI is packaged in both 5 gallon pails and 55 gallon drums, and has a shelf-life of 18 months in unopened containers which are stored in a temperature- and humidity-controlled environment.

The coverage rate of the material will vary slightly from project to project depending on several factors including quality of surface preparation and the density of the existing concrete. The exact amount required for a project depends largely on the present extent of corrosion, chloride ion level and service environment of the structure. A typical application will require 2–3 coats of material at a coverage rate of 175–225 ft²/gal for each coat.

INSTALLATION REQUIREMENTS

SURFACE PREPARATION

The surface preparation required for MasterProtect 8000 CI, though similar, is more involved than the preparation required for typical sealers such as MasterProtect H 1000. All delaminated, loose, or spalled concrete must be removed and repaired prior to commencing the remainder of the surface preparation.

Following repair of any damaged concrete, the substrate must be prepared to an ICRI CSP3 or CSP4 to allow for adequate penetration of the MasterProtect 8000 CI (9). This can be accomplished by abrasive-blasting or abrasive grinding as the project conditions permit. Water blasting is also an acceptable means of surface preparation however adequate time must be provided to allow the concrete to sufficiently dry prior to application. It is recommended to complete a mock-up prior to starting the project to establish the standard surface preparation required to achieve adequate penetration.

Shrinkage cracks that become evident before or after the substrate has been blasted must be evaluated prior to application of MasterProtect 8000 CI. Those that are dormant, shallow in depth and with no structural significance can be treated with multiple coats of MasterProtect 8000 CI. Other cracks should be routed, treated with MasterProtect 8000 CI and finally sealed with the appropriate Master Builders Solutions joint sealant. While MasterProtect 8000 CI does not affect the adhesion of most sealants to concrete; use of Master Builders Solutions sealants and coatings is strongly encouraged to ensure excellent bond and performance.

MasterProtect 8000 CI may be applied directly to exposed reinforcing steel, however it is important to ensure the steel has been cleaned prior to application. While this is an effective repair method, it is still recommended the patch be coated with MasterProtect 8000 CI following the curing of the repair to take advantage of the inhibitor effect of the aminoalkyltrialkoxysilane.

APPLICATION

Apply MasterProtect 8000 CI to the entire surface of the concrete including any repaired areas using multiple coats as required. A minimum of 15 minutes should occur between coats, or until the material is visually dry. Most applications will typically require 2–3 coats.

The material should be applied to the concrete using low-pressure pumping equipment with a wet fan-type spray nozzle. A roller or brush may also be used, and in the case of cracks the MasterProtect 8000 CI may be poured. Do not apply the product to wet or damp substrates, and only at temperatures between 40 and 100° F (5–38° C).

As with MasterProtect H 1000, do not apply MasterProtect 8000 CI if rain is expected within four hours of application, or if high wind or other conditions prevent the material being applied correctly and safely. Allow 24–72 hours for the concrete substrate to dry before application if it is exposed to rain or water blasting.

Considerations must be made when applying MasterProtect 8000 CI prior to the application of urethane based membranes and sealants. During its cure process MasterProtect 8000 CI releases methanol. The presence of any type of alcohol limits the cross linking of these urethane technologies, referred to in the industry as cure inhibition. The alcohol release will affect the cure process and adhesion of the urethane technologies. Application of urethane membranes and sealants may not commence for a minimum of 72 hours following application of MasterProtect 8000 CI.

DRYING TIME

One of the advantages of MasterProtect 8000 CI is that it is a very quick drying material. Under standard temperature and humidity conditions the MasterProtect 8000 CI will be dry to the touch in approximately 6 hours.

Corrosion Monitoring and Testing

Successful implementation of a corrosion mitigation strategy requires ongoing maintenance and evaluation of the repair procedure used. While the products that have been discussed will provide increase protection for many years when properly installed, they are only effective for a finite period of time. Periodic monitoring of the structure should be scheduled to ensure that adequate performance is being achieved. There are a variety of methods that can be employed to ensure that expectations of the products are being met and to identify needs for follow-up maintenance.

Visual Inspection

The simplest and most cost effective method of monitoring a structure is periodic visual inspection. These inspections should be carried out by a qualified individual familiar with the science of corrosion and its effects on concrete. Typical warning signs of corrosion include continued spalling of the concrete, delaminations, and cracking along the lines of the reinforcing steel. While spalls and cracks can be visually inspected, it may be useful to utilize a chain drag to determine if additional delaminations are forming that may not be as readily identifiable by visual inspection.



Figure 20 – Chain Pull Testing for Delaminations – ASTM D4580 Procedure B

Half-Cell Testing

Half-cell testing of the reinforced concrete structure measures the electrical potential of the reinforcing steel in an effort to determine corrosion 'hot-spots'. This testing involves making an electrical connection with the reinforcing steel and a high impedance voltmeter. A copper/copper sulfate or silver/silver chloride half-cell is also connected to the voltmeter and is used to make the half-cell measurements on the surface of the concrete.

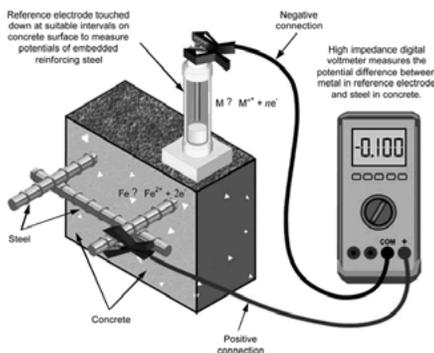


Figure 21 – Typical Half-Cell Testing Device (4)

The process for measuring half-cell potential is discussed in greater detail in the ASTM C876 test method. ASTM C876 suggests that corrosion can only be determined with 95% certainty at potentials more negative than -350 mV, however field testing has shown that potentials more negative than -200 mV likely indicate the onset of corrosion. Note that ASTM C876 considers potentials measured using a copper/copper sulfate electrode.

When using the half-cell test method for evaluating the successful implementation of a repair method it is important to make measurements prior to installation of the corrosion mitigation products and to document the temperature and relative humidity at the time of the initial testing. These initial readings can then be compared to future readings taken under similar environmental conditions to ensure that the half-cell potential readings are more positive following application of the corrosion mitigation product. Also keep in mind that mixed inhibitors, such as MasterProtect 8000 CI, may actually cause the half-cell potential to move to a more negative value as this product functions at both the cathode and the anode. In the case of MasterProtect 8000 CI, additional testing should be done along with half-cell measurements to ensure that the results are accurately understood.

Contour Plot - Car Park, External, 1m Grid

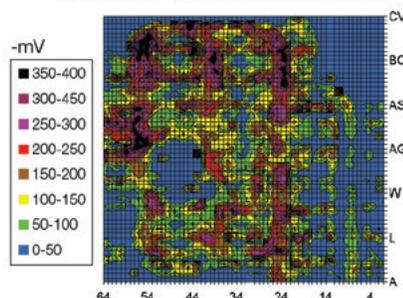


Figure 22 – Typical Plot of Half-Cell Data (17)

Polarization Testing

Several commercially available non-destructive testing devices are available to measure the actual corrosion rate in concrete. These types of devices are particularly useful for monitoring the effectiveness of a product such as MasterProtect 8000 CI, where the half-cell readings may not accurately reflect the condition of the reinforcing steel.

These devices function by inducing a galvanostatic pulse into the concrete to measure the half-cell potential and electrical resistance of the concrete cover. These measurements are used to estimate the corrosion current density by way of the Stern Geary equation.

As with the half-cell testing, an electrical connection must be made between the reinforcing steel and the polarization device. A reference electrode, typically silver/silver chloride, is embedded in a probe, which has a counter electrode on the surface. The difference in potential between the reference electrode and the reinforcing steel is measured to determine the electrical potential of the steel. The ohmic resistance and DC polarization resistance are measured and used in conjunction with the electrical potential to estimate the corrosion current.

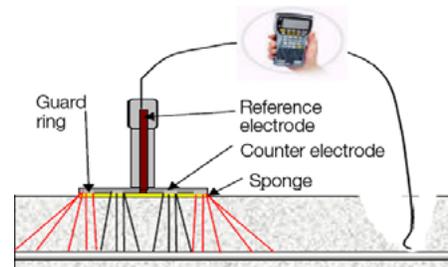


Figure 23 – Typical Polarization Testing Device (18)

Care must be taken when using these types of devices not to make repeated measurements in consolidated areas of the member. Repeated testing in the same location can polarize the steel and lead to inaccurate measurements. Due to the complexities of this device it is recommended that the testing be carried out by a qualified professional knowledgeable in the field of corrosion and proper usage of the device.

Embedded Probes

The most effective means of corrosion monitoring involves the installation of embedded probes. This is most often done in new concrete structures however it is possible to utilize the procedure in concrete repairs as well. These types of systems provide real-time data throughout the life of a structure and most accurately determine the level of active corrosion. They generally involve macrocell current devices set up such that as the electrodes depassivate due to chloride intrusion or carbonation the increased current can be measured and correlated to the corrosion rate. Embedded probes also require additional resources for data collection and monitoring over the life of the structure. However they are widely considered the most effective means of monitoring corrosion of reinforced concrete.

Conclusion

This manual has discussed the basic fundamentals of corrosion in reinforced concrete and introduced the various Master Builders Solutions technologies available for use in combating the ongoing problem of corrosion of reinforcing steel. As we have seen, this is a complex issue that cannot be completely discussed in the brief pages of this manual. The intent of this manual was to provide a basic understanding of corrosion mitigation strategies and Master Builders Solutions corrosion mitigation systems. The introduction to the various corrosion mitigation and prevention systems and fundamentals of corrosion was provided to allow for educated decisions to be made regarding the use of Master Builders Solutions technology as part of a corrosion mitigation strategy. Corrosion in reinforced concrete structures is often the result of a complex matrix of variables, and individual projects should always be evaluated on the basis of their specific needs. Such evaluations should involve a qualified corrosion specialist or engineer to ensure that all potential root causes are determined and the correct solution is provided.

The contents of this manual are intended to provide a fundamental understanding of the solutions available from Master Builders Solutions. For project specific issues that fall outside the scope of this manual, external sources should be consulted.

There is a wide variety of reference material available on the subject of corrosion. ACI, ICRI, and NACE each have collections of corrosion related documents and research. General electrochemistry textbooks are a useful tool for locating additional information relating to the science of corrosion and there are also texts related specifically to the corrosion of reinforced concrete. Several recommended texts are listed on the following pages should a deeper understanding of the concepts discussed in this manual be required.

For additional information relating specifically to the technologies and services offered by Master Builders Solutions, contact your local Master Builders Solutions Sales Professional or Master Builders Solutions Technical Service Department.

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16. <http://www.buildingconservation.com/articles/concrete/concrete.htm>
17. http://www.concrete-testing.com/halfcell_potential.htm
18. <http://germann.org>
19. <http://www.understanding-cement.com/carbonation.html>

Additional Resources

CONTACT MASTER BUILDERS SOLUTIONS

Master Builders Solutions
889 Valley Park Drive
Shakopee, MN 5379

Master Builders Solutions Website: <http://www.master-builders-solutions.com/EN-US>
-Product Information
-Product Datasheets
-Find a Representative

INDUSTRY ORGANIZATIONS

1. American Concrete Institute – www.concrete.org
2. ASTM International – www.astm.org
3. International Concrete Repair Institute – www.icri.org
4. NACE International – www.nace.org

SUGGESTED REFERENCE TEXTS

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2. Corrosion Engineering Handbook. 2nd Edition. Philip A Schweitzer. CRC Press. 2006.
3. Corrosion of Steel in Concrete: Understanding, Investigation and Repair. 2nd Edition. John P. Broomfield. Spon Press. 2006.

1
B-1065

TYP. INSTALL AT BAR INTERSECTION
SCALE: N.T.S.

2
B-1065

TYP. INSTALL BELOW BAR
SCALE: N.T.S.

NOTES:

1. REMOVE DAMAGED CONCRETE AND PREPARE SURFACE OF EXISTING CONCRETE PER ICRI GUIDELINE NO. 310.1R-2008.
2. COMPLETELY CLEAN THE EXPOSED REINFORCING STEEL OF CORROSION PRODUCT. REPLACE STEEL AS REQUIRED.
3. ENSURE THAT ALL EXPOSED REINFORCING STEEL IS SECURELY FASTENED TOGETHER WITH TIE WIRES TO PROVIDE GOOD ELECTRICAL CONDUCTIVITY.
4. ATTACH MasterProtect® ANODES TO CLEAN REINFORCING STEEL AT AN EVEN SPACING WITHIN THE PATCH AREA. REFER TO BASF DETAILS B-1066 FOR MAXIMUM SPACING GUIDELINES.
5. PLACE NEW CONCRETE REPAIR MORTAR INTO THE REPAIR AREA PER PROJECT REQUIREMENTS. OBSERVE ELECTRICAL RESISTIVITY LIMITS ON REPAIR MORTARS AND BONDING AGENTS USED.

3
B-1065

TYP. INSTALL BESIDE BAR
SCALE: N.T.S.

<small>CURRENT ISSUE DATE:</small>	<small>DRAWN BY:</small>	STANDARD DETAIL
15 JAN 2014	WJG	
<small>DATE CREATED:</small>	<small>CHECKED BY:</small>	MasterProtect® Anodes
22 OCT 2009	WJG	TYPICAL INSTALLATION DETAILS
<small>DRAWING NO:</small>		
B-1065		
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3" MIN. FOR MasterProtect® 8105 CP & MasterProtect® 8150 CP ANODES

2.75" MIN. FOR MasterProtect® 8065 CP ANODE

1" MIN. TO TOP OF ANODE

1" MAX

MasterEmaco® REPAIR MORTARS BY BASF.

MasterProtect® ANODE INSTALLED ONTO EXISTING REINFORCING STEEL

EXISTING CONC. SUBSTRATE

<small>CURRENT ISSUE DATE:</small>	<small>DRAWN BY:</small>	STANDARD DETAIL
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03 MAY 2011	BJS	MINIMUM ANODE COVER & EDGE DISTANCE
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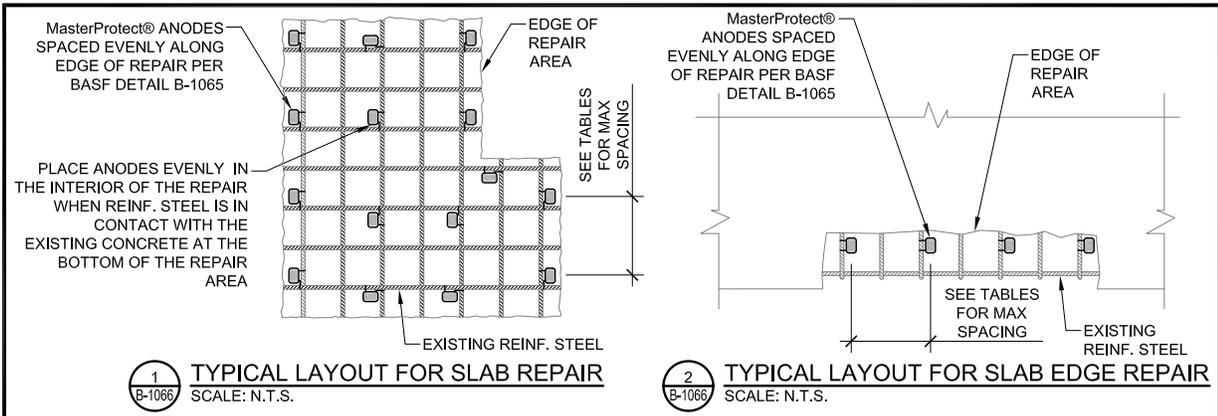


TABLE A - CORRODED BARS

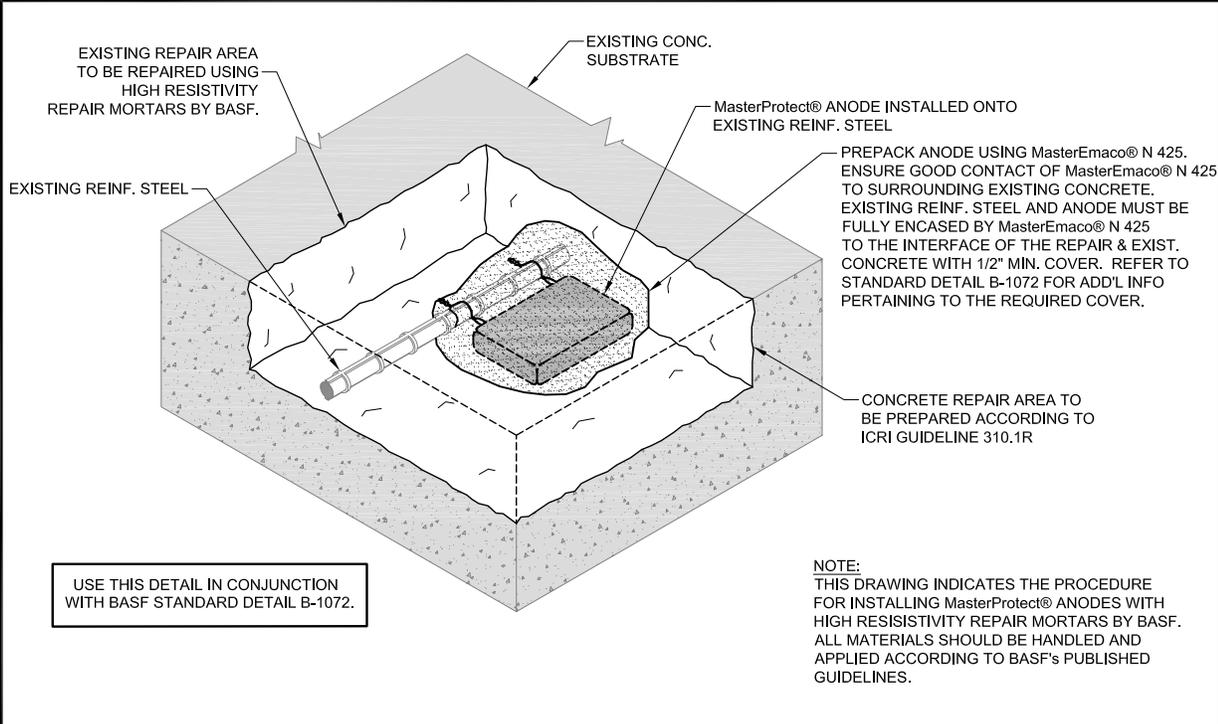
STEEL DENSITY RATIO	MAX. SPACING (IN)
<0.20	28
0.21 - 0.40	24
0.41-0.54	20
0.55 - 0.67	18
0.68 - 0.80	16
0.81 - 0.94	15
0.95 - 1.07	14
1.08 - 1.20	13

TABLE B - NON-CORRODED BARS

STEEL DENSITY RATIO	MAX. SPACING (IN)
<0.30	30
0.31 - 0.60	28
0.61 - 0.90	26
0.91 - 1.20	22
1.21 - 1.50	20
1.51 - 2.00	17

NOTE: STEEL DENSITY RATIO IS THE RATIO OF STEEL REINFORCING BAR SURFACE AREA TO EXPOSED CONCRETE SURFACE AREA IN THE REPAIR ZONE.

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