Corrosion in Concrete

TECHNICAL REPORT

Table of Contents

Introduction

Corrosion is a costly global issue, accounting for an estimated 3% of the U.S. GDP due to its impact on infrastructure, transportation and industry. In the USA alone, corrosion-related repairs and maintenance costs run into the billions of dollars annually. When repairs to corroded structures are delayed or neglected, the costs escalate significantly, as damage becomes more extensive and difficult to address. Without timely intervention, corrosion accelerates the deterioration of concrete and steel, leading to more frequent and severe failures. This not only increases maintenance expenses but also results in higher costs for rehabilitation or replacement, putting a strain on budgets as well as risking safety and service disruptions.

Corrosion in concrete primarily affects the embedded steel reinforcement, leading to significant structural and aesthetic damage. As steel corrodes, it forms rust, which expands and creates internal pressure within the concrete. This pressure causes cracking and spalling, where pieces of the concrete surface break away, exposing more of the steel to corrosive elements. Over time, the loss of concrete cover and the weakened steel reinforcement reduce the structural capacity of the building, making it less safe and more prone to failure. Additionally, corrosion-related damage diminishes the aesthetic appeal of the structure, as visible cracks, rust stains and spalled surfaces indicate deterioration and neglect.

MAPEI Corporation offers a full range of corrosion mitigation products, including sealers, coatings, chemical treatments and galvanic anodes. This guideline explains how these technologies work, their best applications and detailed installation considerations, ensuring informed decision-making in corrosion prevention and repair.

Corrosion basics

Definition of corrosion

Corrosion in concrete is the deterioration of embedded steel reinforcement caused by chemical reactions between the metal and its surrounding environment. This process leads to cracking, spalling and weakening of the concrete, compromising the structure's integrity.

Oxidation

The formation of rust on reinforcing steel is due to the oxidation of the iron atoms that make up the steel rebar. When a material is oxidized, it means that it has lost at least one electron while interacting with another atom. By giving up electrons, the iron becomes a positively charged ion. Visually this is shown as $Fe \rightarrow Fe^{2+} + 2e^-$.

Reduction

Reduction is simply the opposite of oxidation, meaning an atom gains at least one electron. In the case of reinforced concrete, the free electrons from the oxidation of the iron bond with both oxygen and water to form negatively charged hydroxide ions.

Electrochemical reaction

This transfer of electrons from one atom to another generates an electric current. When considering corrosion, the current formed from the redox reaction is the corrosion current. The higher this current, the more severe the corrosion. The rate at which this transfer occurs is the corrosion rate, and again the higher the rate, the more severe the corrosion of the reinforcing steel.

Electrical resistivity

All materials have what is referred to as electrical resistivity. Electrical resistivity is a measure of a material's resistance to the flow of electric current. Materials with higher electrical resistivity will slow the flow of electrons occurring during the redox reactions of the corrosion process, thereby lowering the rate of corrosion. It is for this reason that in most cases, concrete repair materials with a higher resistivity are preferable.

Electrolyte

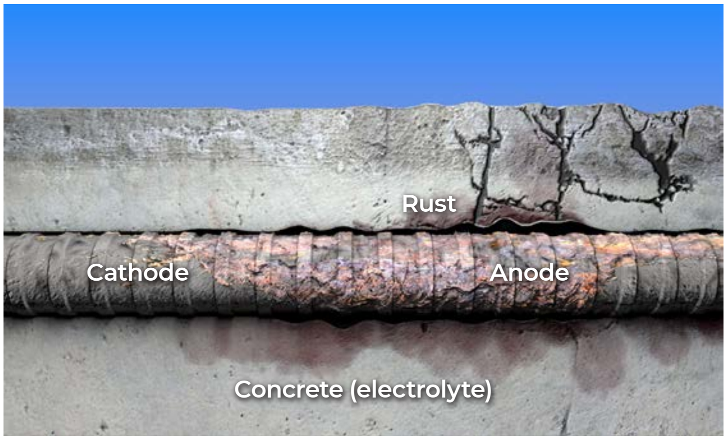
The electrolyte is the material (concrete, soil or water) in contact with both the anode and the cathode that allows ionic current flow to occur between the anode and the cathode.

Concrete acts as an electrolyte with its connected pores systems filled with water and oxygen.

Most often, the easiest solution to control corrosion is by preventing the concrete from acting as an electrolyte by keeping the concrete dry. The concrete also needs a connected network of pores; this is also why dense concrete – such as concrete modified with silica fume, with latex or with a low water and binder ratio – offers better resistance to corrosion.

Anode

The anode is where the oxidation reaction takes place. As shown below, the iron reacts with the water and the chloride to form rust, such as $Fe(OH)_2$. Rust has a higher volume than the steel, which causes the rebar to expand. Since concrete has a low resistance to traction, an internal expansion leads to various failures such as cracking and delamination, and can also lead to loss of structural capacity due to the reduction of the steel rebar section. When we see damage in concrete like rust staining, cracking and delamination, these are anodic locations where the reinforcing steel is expanding due to corrosion and causing deterioration in the concrete.



Cathode

This is where the reduction reaction of the iron with the oxygen, water and liberated electron from the anode takes place, as shown above. Hydroxides (OH-) are liberated in the concrete matrix, which then migrates to the anode to react with the reduced iron.

There are no visual or detrimental effects at the cathodic location.

Types of corrosion

Pitting corrosion

Pitting corrosion in concrete typically starts when chloride ions penetrate the concrete and break down the protective passivation layer on reinforcing steel, leading to localized corrosion that creates small, deep pits. Those pits can weaken the structural integrity of the concrete and lead to severe damage if left untreated.

Galvanic corrosion

Galvanic corrosion in concrete occurs when two dissimilar metals, such as steel rebar and aluminum, are in electrical contact in the presence of an electrolyte-like moisture. This causes the more reactive metal (anode) to corrode faster, which can lead to premature deterioration of the concrete and compromised structural performance.

Causes of corrosion in concrete

Chloride-induced corrosion

Chloride-induced corrosion is an electrochemical process that is detrimental to reinforced concrete structures when left untreated. In order to treat chloride-induced corrosion, it is essential to have a basic understanding of the electrochemical process that is occurring.

Once the chloride concentration has exceeded the threshold, or the pH of the concrete becomes sufficiently low to allow for chloride-induced corrosion, the electrochemical process can begin.

Carbonation

Carbonation in concrete occurs when carbon dioxide from the air penetrates the concrete and reacts with calcium hydroxide, reducing the pH and compromising the protective passivation layer around the steel reinforcement, which increases the risk of corrosion and can lead to structural degradation.

Chemical attack

Sulfates are a common cause of corrosion in reinforcing steel, particularly in wastewater treatment plants. While sulfates themselves don't rust steel, they create conditions favorable for chloride-induced corrosion. Sulfates can come from external sources, such as clay soils, acid rain, bacterial sulfuric acid in sewers, and seawater. Internal sources, like high-sulfate aggregates or excessive gypsum in cement, can also contribute but are more easily controlled through material testing. Sulfates accelerate concrete deterioration, leading to cracks that allow chlorides to penetrate and initiate corrosion.

Corrosion mitigation strategies

Corrosion prevention and corrosion protection

Corrosion protection and corrosion prevention are often confused, but they represent distinct strategies. Prevention occurs before corrosion starts, while protection is implemented in the early stages when some corrosion is present but not widespread. The goal of protection is to limit damage to affected areas and safeguard the rest of the structure.

Corrosion prevention strategies can be highly effective in delaying the onset of corrosion when properly maintained and managed. However, it is generally not feasible to prevent corrosion indefinitely. Once corrosion begins, simply sealing the surface to block moisture will not stop the ongoing corrosion. Moisture, along with chlorides, acts as both a reactant and a product in the electrochemical corrosion process. Once moisture has entered and initiated reactions, it remains unless the concrete can be thoroughly dried, which is difficult to achieve in practice.

While MAPEI offers a range of products for corrosion prevention, additional options outside the MAPEI product line include but are not limited to stainless steel rebar, polymer fiber-reinforced rebar and epoxy-coated bars. Engineers and owners should carefully consider the balance of risk and cost when selecting corrosion prevention methods, but a system-based approach typically provides the most effective results.

When reinforced concrete has visible damage cause by corrosion, the standard practice is to remove the damaged concrete, clean the steel reinforcement thoroughly and patch the area with repair mortar.

Halo effect

The halo effect can be described as a reversal of the cathode and anode roles. In a typical repair scenario, the anode (located where concrete spalling or cracking has occurred) is adjacent to a cathode in sound concrete where no damage is apparent. Without implementing protective measures during the repair, the previous anode becomes embedded in the newly repaired concrete with a low potential, while the former cathode, which remains in high-potential existing concrete adjacent to the repair, becomes the new anode. This reversal creates a new and more aggressive corrosion cell, leading to further damage around the perimeter of the repair patch.

To prevent the halo effect, a corrosion protection strategy is essential. Several MAPEI products are designed to mitigate this issue, such as *Mapeshield™ I* galvanic anodes that prevent the halo effect by utilizing the lower nobility of zinc compared to steel, causing the galvanic anode to become the anode in the corrosion cell instead of the surrounding steel. Other solutions are presented in the section "MAPEI's corrosion solutions" on Page 10.

Corrosion mitigation

The key difference between corrosion protection and corrosion mitigation is that protection targets small areas of corrosion, while mitigation covers the entire structure.

There are two main technologies for corrosion mitigation: Surface-applied inhibitors and impressed current cathodic protection (ICCP) systems. Both can be applied locally but are typically used across the entire structure. The primary distinction of mitigation technologies is their ability to reduce active corrosion, unlike prevention and protection that either prevent corrosion or redirect it to a sacrificial location.

ICCP systems reduce corrosion by passing current through the reinforcing steel, reversing the roles of anode and cathode. They are highly effective and considered the gold standard for reducing active corrosion, though they require ongoing monitoring and involve significant external wiring. While expensive, not aesthetically pleasing and a headache to monitor and maintain, ICCP systems are the best solution for critical structures.

MAPEI's primary corrosion mitigation products are the surface-applied migrating corrosion inhibitors *Mapeshield CI 100* and *Mapeshield CI 110*. Both are clear liquids applied to new or existing concrete surface by rolling or spraying. These migrating corrosion inhibitors penetrate the concrete and migrate to the reinforcing steel, where they restore the protective passivation layer and increase the threshold of chloride content necessary to activate corrosion, thus preventing further damage. *Mapeshield CI 100* is a single-component inhibitor, while *Mapeshield CI 110* includes an added water repellent, making it a dual-component inhibitor.

Both inhibitors are highly effective, provided that the steel is reached. *Mapeshield CI 100* has been successfully used in numerous projects, while *Mapeshield CI 110* is favored for projects that require more testing, such as government work. Regardless of the product selected, MAPEI guarantees the highest quality of corrosion mitigation solutions with proven performance.

Cathodic protection design

According to the report of the Federal Highway Administration, cathodic protection (CP) is the only rehabilitation technique that has been proven to stop corrosion in concrete structures contaminated by chlorides, regardless of their concentration. By applying CP, the corrosion potential is shifted into the immunity zone and, from a practical point of view, corrosion is stopped.

A CP design utilizing galvanic anodes takes the following factors into account:

- Steel density ratio: Surface area of the reinforcing steel that needs protection in relation to surface are of concrete
- Annual average temperatures: Every 18˚F increase in the annual average temperature causes the corrosion rate to double.

- Exposure class and chloride concentration: An increase in chloride levels will require a higher current output from galvanic anodes.
- Expected durability: Desired service life of galvanic anodes
- Current distribution: Ensuring uniform current flow to protect all areas of the steel

MAPEI's corrosion solutions

This following section outlines the corrosion solutions offered by MAPEI. Be sure to reference all published technical data sheets and safety data sheets prior to working with these products and technologies. And, as always, be sure to utilize all recommended safety gear.

Water repellents

Planiseal® WR 100 is a clear, high-performance, 100%-silane, penetrating water repellent and sealer designed to provide water repellency on concrete and masonry. It penetrates deeply, reacts with concrete hydrate and increases the water contact angle in the concrete pores, making them hydrophobic and thus protecting new and existing substrates against moisture/chloride intrusion.

Where to use

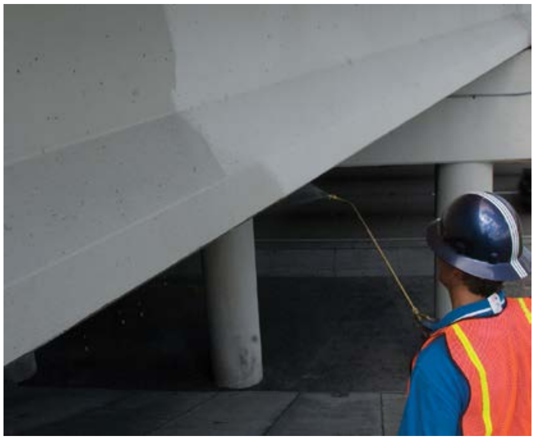
- Parking, bridge and stadium decks
- Sidewalks and ramps
- Above-grade, interior/exterior, horizontal and vertical surfaces
- New and existing concrete, block, stone and brick

Features and benefits

- 100%-silane, protecting against water absorption and chloride ion intrusion
- Colorless and does not alter surface appearance or texture
- Breathable, allowing interior moisture to escape
- Easy-to-apply, one-component water repellent

MAPEI also provides *Planiseal WR 40*, a 40%-silane penetrating water repellent and sealer. The lower percentage of silane is commonly used for moderate and less critical applications and/or larger areas due to it being more economical than the 100%-silane treatment.

Planiseal WR is a silane/siloxane-blend, water-repellent, transparent sealer that provides resistance to water, dirt and chlorides. Siloxanes provide a more durable, film-forming water-repellent barrier , whereas silanes have smaller molecules that penetrate deeper into substrates like concrete. *Planiseal WR* utilizes the benefits of both the silane and siloxanes for protecting concrete.



Where to use

- Properly prepared, sound and stable concrete substrates (at least 28 days old)
- Concrete driveways and sidewalks, concrete pavers and block
- Use on vertical or horizontal surfaces.

Features and benefits

- Penetrates deep into the substrate for long-lasting protection
- Improves cleanliness of concrete by reducing dirt pickup
- Provides water repellency to concrete and masonry
- *Planiseal WR* is breathable, allowing interior moisture to escape.
- Water-based composition provides low odor and VOC compliance.
- Reduces efflorescence

Rebar coatings

Mapefer™ *1K* is a one-component, anti-corrosion coating based on unique polymers, cementitious binders and corrosion inhibitors. *Mapefer 1K* is specially formulated for application on properly prepared reinforcing steel to inhibit oxidation and rust formation.

Planibond® *3C* is a three-component, cementitious, moisture-tolerant, epoxy-modified corrosion inhibitor and bonding agent. Water-based and solvent-free, it can be applied using a brush, a short-nap roller, a push broom or hopper spray equipment. Use *Planibond 3C* on all exposed reinforcing steel and as a bonding agent before the placement of repair products.

Where to use

- For corrosion-inhibiting protection of reinforcing steel in concrete

Features and benefits

- High in density and alkalinity, *Mapefer 1K* and *Planibond 3C* offer excellent resistance to chloride penetration, carbon dioxide penetration and pollutants.
- Contain corrosion inhibitors
- Increase the barrier against water and chlorides

Sacrificial galvanic anodes

Mapeshield I is a pure zinc anode for cathodic protection of reinforcing steel against corrosion in new, reinforced structures as well as structures requiring repair.

Where to use

- For corrosion-inhibiting protection of reinforcing steel in concrete
- On new, steel-reinforced concrete structures and elements that will be affected by chloride ingress
- On existing, steel-reinforced concrete that exhibits corrosion from chlorides
- Can be installed in architectural precast before placement of concrete

Features and benefits

- Available in different weights of active zinc content
- Surrounded by a special conductive paste, *Mapeshield I* anodes provide sufficient current to be anodic to the reinforcing steel and lower in electric resistance than other anodes that have solid, thick cementitious shells.
- An optimized design that maximizes the available surface area of the zinc plates

- Does not require a low-resistivity mortar packed around the anode when a high-resistivity repair mortar is utilized
- Thinnest profile on the market: The thin profile of the *Mapeshield I* anode allows for its use in very shallow repairs.
- Compliance with international standard ISO 12696, “Cathodic Protection of Steel in Concrete”

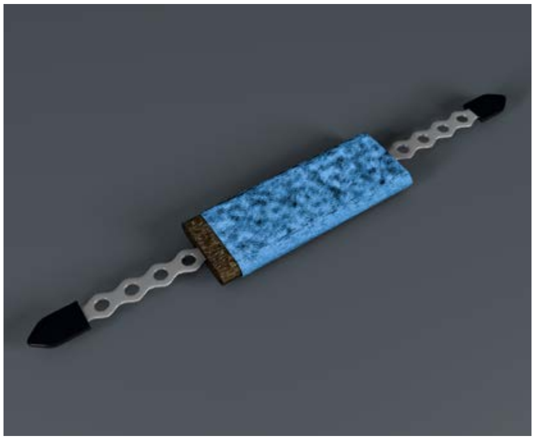
Metals can be classified according to their nobility (that is, according to their ability to yield electrons). The more noble a metal is, the more difficult it will be to yield and thus oxidize.

CORRODED END
(anodic or less noble)

Magnesium
Zinc
Aluminum
Steel
Lead
Tin
Nickel
Brass
Bronzes
Copper
Stainless steel (passive)
Silver
Gold
Platinum

PROTECTED END
(cathodic or more noble)

Sacrificial galvanic anodes are based on the coupling of two different metals within an electrolyte: The carbon steel of which the reinforcing bars are made and the zinc of the anodes. By electrically connecting the galvanic anode to the reinforcing steel, a direct current is generated that lowers the electrical potential of the steel and protects it from corrosion. The metal with the most negative electrical potential oxidizes (anode), protecting the metal with the least negative potential (cathode) so that it remains protected. The zinc in the sacrificial anodes oxidizes over time, sacrificing itself in favor of the reinforcement inside the concrete, thus delaying the initiation of the corrosion process. Although several metals (magnesium, zinc and aluminum) can be used as sacrificial metals to protect steel, only zinc should be used in concrete applications because when it corrodes, it does not have significant volumetric expansion, which helps minimize the risk of additional tensile stresses that could crack or damage the surrounding concrete.



Mapeshield I anodes are designed with a multilayer zinc core and not with a single mass of zinc. The surface area of the zinc is a crucial parameter to ensure that the anode effectively polarizes the reinforcing steel. A multilayer zinc core has approximately triple the zinc surface area compared to anodes with a single mass core.

Another aspect that characterizes and enhances the operation of *Mapeshield I* anodes is the conductive gel with which they are coated – an electrolytic material consisting of water-based acrylic binders, conductive ions, a pH regulator and an inert filler material. This innovative material ensures that the anode functions in environments with low humidity as well as in alkaline environments, such as concrete, as it prevents zinc passivation and thus anode malfunction.

Repair mortars compatible with *Mapeshield I* galvanic anodes

The concrete or the repair mortar in which the *Mapeshield I* is embedded must be below an electrical resistance of 100kΩ-cm to ensure proper electrical conductivity. This value can be interpreted from results from ASTM C1202, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration."

The table below can be used to correlate the resistivity of the concrete from the rapid chloride penetration test (RCPT) results.

Concrete typically has a resistivity varying between 1 and 15k ohm-cm. It should be noted that external factors other than the formulation of concrete can affect the resistivity. Most importantly, a decrease in temperature will increase the resistivity, as well as decrease the internal humidity of the concrete. In conclusion, a more porous and more humid concrete will have a lower resistivity.

Chloride Penetration	Surface Resistivity (kΩ-cm)	Bulk Resistivity (kΩ-cm)	Rapid Chloride Permeability Test (coulombs)
High	< 10	< 5	< 4,000
Moderate	10 to 15	5 to 10	2,000 to 4,000
Low	15 to 25	10 to 20	1,000 to 2,000
Very low	25 to 200	20 to 200	100 to 1,000
Negligible	> 200	> 200	< 100

Below is a list of MAPEI repair mortars that can be used in conjunction with *Mapeshield I* galvanic anodes:

Product	Resistivity (ohm-cm)	Repair type	Note	Compressive strength in 24 hours
Planitop® 11	< 15,000	Full-depth form-and-pour	Pre-extended; good for large volume and full depth repairs	> 2,500 psi
Planitop 11 SCC	32,000	Full-depth form-and-pour	Self-consolidating, full-depth repairs	> 2,200 psi
Planitop 12 SR	30,000	Vertical, overhead, horizontal	Sulfate-resistant; can be sprayed or pumped	> 2,900 psi
Planitop 15	63,000	Form-and-pour	High early strengths; great for marine environments	> 4,350 psi
Planitop 18	23,000	Horizontal	Very rapid-hardening; high early strengths; great for DOT projects	> 7,800 psi
Planitop 18 ES	25,000	Horizontal	Very rapid-hardening with extended working time; great for bridge decks	> 5,000 psi
Planitop X	12,000	Vertical and overhead	Fast-setting; high-build	> 5,600 psi
Planitop XS	30,000	Vertical and overhead	Fast-setting; extended working time	> 3,000 psi

Refer to MAPEI's Technical Data Sheets for mixing and placement instructions.

Steel density ratio

The steel density ratio plays a pivotal role in the strategic placement of galvanic anodes during concrete repairs. By accurately assessing the steel density, engineers can determine the appropriate spacing of galvanic anodes to provide targeted cathodic protection. This method prevents localized corrosion by ensuring that the anodes distribute protective currents evenly across the reinforced concrete structure.

This steel density ratio is the surface area of the reinforcing steel in relation to the surface area of the concrete. Typically, this is done by looking at the size and number of steel reinforcing bars in 1 square foot of concrete.

$$\text{Steel density ratio} = \frac{\text{Surface area of steel}}{\text{Surface area of concrete}} = \frac{\pi \times D \times L \times n}{144 \text{ in}^2}$$

D = diameter of steel reinforcing bar (in.)

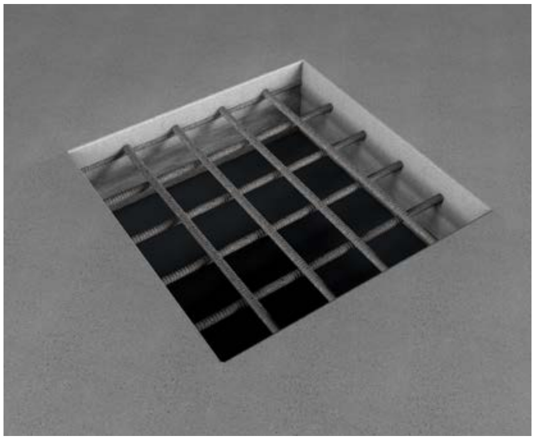
L = Length of steel reinforcing bar within the calculated area
(12" in this example, since we are looking at 1 sq. ft. of concrete area)

n = Total number of steel reinforcing bars within the calculated area

The example below demonstrates how to calculate the steel density ratio. Tables included in MAPEI's Technical Data Sheet for *Mapeshield I* provide the maximum spacing corresponding to the calculated steel density ratio.

Calculation examples

Example 1: Typical slab:
#5 bars @ 12" o.c. each way (top and bottom mats)



Top mat transverse bars:
$(\pi \times D \times L \times n) / 144 \text{ in}^2 = (\pi \times 5/8” \times 12" \times (12/12)) / 144 \text{ in}^2 = 0.16$

Top mat longitudinal bars:
$(\pi \times D \times L \times n) / 144 \text{ in}^2 = (\pi \times 5/8 \times 12") \times (12/12) = 0.16$

Total steel density ratio = Top mat of bars + bottom mat of bars

Top mat of bars = 2 x 0.16 = 0.32

Bottom mat of bars = 2 x 0.16 = 0.32

Total steel density = 0.32 + 0.32 = 0.64

Required spacing (presuming repair):

Mapeshield I 70 or *Mapeshield I 10* = 22" o.c.

Mapeshield I 30 = 30" o.c

Structures Requiring Repair – Maximum Spacing (on center)**

Density of Reinforcing Steel*	*Mapeshield I 70*	*Mapeshield I 105*	*Mapeshield I 10*	*Mapeshield I 30*
0.6	~24" (60.9 cm)	~24" (60.9 cm)	~24" (60.9 cm)	~32" (81.2 cm)
0.8	~20" (50.8 cm)	~20" (50.8 cm)	~20" (50.8 cm)	~28" (71.1 cm)
1.0	~16" (40.6 cm)	~16" (40.6 cm)	~16" (40.6 cm)	~24" (60.9 cm)
1.2	N/A	~12" (30 cm)	~12" (30 cm)	~20" (50.8 cm)
1.4	N/A	~8" (20 cm)	~8" (20 cm)	~16" (40.6 cm)

** Actual surface area of reinforcing steel rods per square foot (0.09 m^2) of concrete*

*** Maximum spacing is based on typical conditions*

Example 2: 12" square concrete column

(4) #7 vertical bars and #4 ties at 12" o.c.

Vertical Bars: (π x D x L x n) = (π x 7/8" x 12" x 4 sides) = 131.96 sq. in.

Ties: (π x D x L x n) = (π x 4/8" x 8" x 4 sides) = 50.27 sq. in.

Concrete surface area:
(12" x 4 sides x 12" height) = 576 sq. in.

Total steel density ratio = (131.96 sq. in. + 50.27 sq. in.) / 576 sq. in. = 0.32

Required spacing (presuming new construction)

Mapeshield I 70 or *Mapeshield I 10* = 36" o.c.

Mapeshield I 30 = 40" o.c.

Mapeshield design software

For the design of the galvanic cathodic protection system, MAPEI has developed its own user-friendly software, in line with the specifications of the *Mapeshield* product line. The program can be freely used to estimate the number and type of anodes required based on a series of input data, following the procedure described above.

MAPEI's Technical Services Department as well as our experienced specialists and engineers certified in cathodic protection are ready to provide any technical support in this field.

Migrating surface-applied corrosion inhibitors

Mapeshield CI 110 is a surface-applied corrosion inhibitor, with an integrated moisture repellent, designed to penetrate concrete and protect embedded steel reinforcement. *Mapeshield CI 100* delays the corrosion process, reduces overall corrosion activity and creates a water-repelling barrier on the surface of the concrete.

Where to use

- Steel-reinforced concrete such as in bridges, highways and parking structures
- Marine structures, such as piers, piles and concrete docks
- Concrete-framed building facades and balconies
- Tunnels and other underground structures
- Wastewater treatment tanks
- Concrete pipes and utility poles

Features and benefits

- Environmentally friendly with its nonflammable formula
- Helps to passivate embedded steel against corrosion by penetrating into concrete

- Reduces existing corrosion, enhancing the durability of reinforced concrete
- Compatible with MAPEI repair mortars
- Not a vapor barrier; allows concrete to breathe
- Applied by roller, brush or spray
- Does not require removal of good-quality concrete

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