The Case for Cathodic Protection of Concrete in Aggressive Environments

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Reinforced concrete structures are designed and built to function for a certain period of time (service-life) with as little maintenance as possible. In benign environments, the structure achieves its service-life with little or no major repairs needed. However, as the infrastructure ages, we are continuously looking to extend its service-life rather than to replace it. This is especially true for high value assets and structures that cannot be taken out of service easily. The more aggressive the environment is, the more likely the need for repair as service-life of these structures is stretched. Unfortunately, due to budget constraints or lack of understanding of repair options, owners of infrastructure often take a short-term repair approach rather than a long-term repair and protection approach.

The decision on how to perform a repair might seem straightforward, but it is not always the case. Huge resources are required to detail the design and execution of such repair methods. Questions such as what to repair, to what extent, what is the impact on the operation, and how to best use the available budget on technologies capable of extending the life of the structure, need to be answered as clearly as possible.

An important first step for owners is to define what service-life means for a particular structure in terms of performance, safety, downtime and even appearance. An industrial facility or coal dock owner will view the aesthetics of their structures as a low priority as long as the loading capacity of the dock and full operation is maintained. On the other hand, a cruise line operator would want a more aesthetically pleasant looking dock for clients boarding their mega cruise ships. Hence, they cannot tolerate the level of deterioration a coal dock owner will and therefore have a different definition of service-life for their dock.

Once the service-life requirement is defined, the repair plan can be tailored to fulfill these requirements within budget, and operational and feasibility constraints. First, the objective of the repair has to be defined, the quantities of the repairs have to be estimated, and the technology used to implement the repair has to be selected. The last stage may include an analysis of conventional repair methods versus technology-driven repair methods to ensure the structure is repaired with minimal disruption service-life of the operation of the structure.

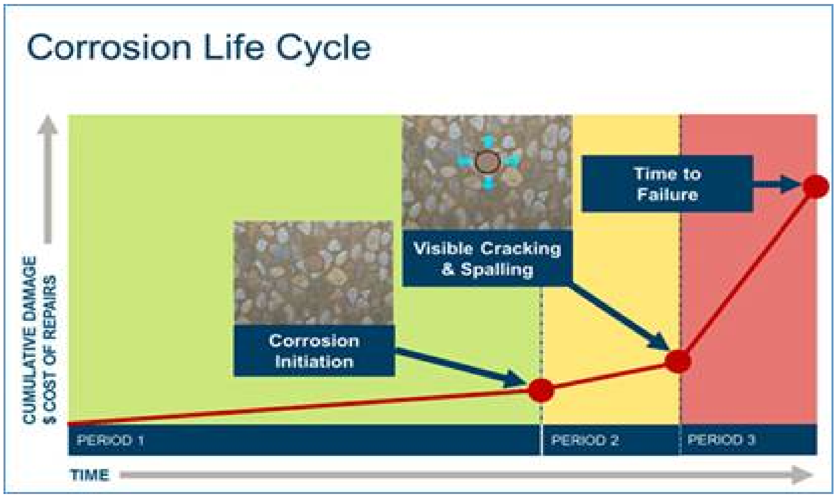
The environment in which the structure operates plays a crucial role in selecting the technology most suited to extending its service-life. A deeply carbonated cover or high chloride contamination close to rebar depth will further narrow the choice of applicable technologies that would deliver the target service-life. ACI 319-11 provides a method of classifying and categorizing the different exposure environments a concrete structure can be exposed to. As shown in table 1, the environments that affect the steel reinforcement vary in severity. Of particular interest are classes C1 and C2 where the concrete is susceptible to moisture or moisture with an external source of chloride, causing the corrosion damage to the reinforcement and eventually the entire structure, if left unattended.

Table 1 - Exposure categories and classes (ACI 319-11)

Category	Severity	Class	Condition	
Freezing and thawing (F)	Not applicable	F0	Concrete not exposed to freezing-and-thawing cycles	
	Moderate	F1	Concrete exposed to freezing-and-thawing cycles and occasional exposure to moisture	
	Severe	F2	Concrete exposed to freezing-and-thawing cycles and in continuous contact with moisture	
	Very severe	F3	Concrete exposed to freezing-and-thawing cycles and in continuous contact with moisture and exposed to deicing chemicals	
Sulfate (S)	**Severity**	**Class**	**Water soluble sulfate (SO_4) in soil, percentage by mass***	**Dissolved sulfate (SO_4) in water, ppm†**
	Not applicable	S0	$SO_4 < 0.10$	$SO_4 < 150$
	Moderate	S1	$0.10 \leq SO_4 < 0.20$	$150 \leq SO_4 < 1500$ or seawater
	Severe	S2	$0.20 \leq SO_4 \leq 2.00$	$1500 \leq SO_4 < 10,000$
	Very severe	S3	$SO_4 > 2.00$	$SO_4 > 10,000$
Requiring low permeability (P)	Not applicable	P0	In contact with water where low permeability is not required	
	Required	P1	In contact with water where low permeability is required	
Corrosion protection of reinforcement (C)	Not applicable	C0	Concrete dry or protected from moisture	
	Moderate	C1	Concrete exposed to moisture but not to an external source of chlorides	
	Severe	C2	Concrete exposed to moisture and an external source of chlorides from deicing chemicals, salt, brackish water, seawater, or spray from these sources	

The selection of technology type to use to face the onslaught of chloride induced corrosion depends primarily on the stage of corrosion the structure is in. A low chloride penetration depth means that a technology that limits access of chlorides into the structure's surface - such as sealers and coatings - will slow down the chloride migration process and extend the service-life of the structure. It acts as a physical barrier that makes it harder for chloride ions to reach the concrete pore structure. However, as with any physical barrier applied on the surface of the concrete, imperfections in the application are inevitable. Even if the application of barrier technologies is almost perfect, all coatings, membranes, and sealers degrade over time. In other words, the best protection a coating will provide is on the first day of its application. For coatings, membranes, and sealers to be effective, continuous inspection, maintenance, and reapplication is required. Although coatings are usually seen as a cheaper initial investment to alternative repair methods, maintenance of such coatings and sealers is often overlooked and becomes one of the first items to be cut out of maintenance budgets.

Structures are rarely slated for repair when little to no chloride contamination or low carbonation at the rebar is expected or measured. Usually, corrosion is fully initiated by either high chloride contamination or deep carbonation. Once corrosion induced damage to the structure is detected, owners and operators realize that their concrete structure requires attention.

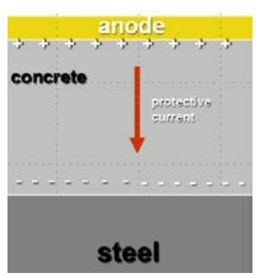


Unfortunately, by the time damage is visible in some areas of a structure, the carbonation or chloride concentration throughout the entire structure may have created an environment where corrosion is silently occurring in areas that look perfectly sound. Only addressing the areas that show severe deterioration and delaying repairs on areas of the structure that are not yet showing signs of distress, results in an ongoing repair cycle that may have lower initial cost of repair, but higher life-cycle cost of repair.

Even when the need to address the issue of ongoing corrosion throughout a structure is recognized, the method of protection may not be appropriate based on the degree of contamination. For example, coatings and sealers can be an effective protection strategy in some cases but once a structure has reached a certain level of contamination such solutions can be ineffective. A different approach is needed to counter the electrochemical attack that is caused by chlorides or carbonic acid reaching the steel reinforcement depth.

One proven technology is cathodic protection (CP). It can be installed during the construction phase on a new structure, or as part of a repair solution aimed at extending the service-life of the structure. The Strategic Highways research program in their 1993 report stated that "Cathodic Protection (CP) has proven itself as the only permanent repair of existing corroded steel reinforced concrete. Therefore, CP must not be considered separately, but as a part of a complete rehabilitation program" (1993 Strategic Highways Research Program (SHRP) Report, S-337).

CP is defined as a technique used to control the corrosion of a metal surface by making it the cathode of an electrochemical cell. This is achieved by injecting a low direct current (DC) onto the reinforcement through the concrete. The steel reinforcement is then considered cathodically protected. The current source can come from an external power supply and be delivered via a geometrically stable anode, or it can come from a sacrificial metal such as zinc installed within or on the concrete surface that delivers the protective current by sacrificing itself (corroding).



The reason CP is such an effective and practical method to mitigate corrosion induced damage to reinforcement steel is due to its active technology that can change the electrochemical reactions occurring on the surface of the steel. CP, when designed and operated correctly, nullifies the effect of chloride or carbonation-induced corrosion by maintaining and restoring the passivation layer on the steel reinforcement within the concrete. No other method is capable of reversing the damaged caused to the passivation layer of the steel reinforcement with such efficiency for an extended period of time. CP by means of an impressed current (ICCP) can be designed to mitigate corrosion for extreme levels of contamination and continuous exposure to contamination without the need of any physical alteration to the system. Such versatility, offered by state-of-the-art power supplies and monitoring equipment capable of delivering milliamp precision protection currents, has made CP a viable solution for protection of reinforced concrete structures in aggressive environments.

In industrial facilities, cooling towers that utilize sea or brackish water as a cooling medium face aggressive environments. The abundance of chlorides, moisture, humidity, and oxygen, along with elevated temperatures offer the optimum circumstances for corrosion damage to occur at a high rate. An example of effective CP, ICCP in particular, is a project in which a mechanical draft cooling tower basin was in need of repair as it showed significant signs of leaks, cracks, delaminated concrete, and corrosion. The tower processes seawater as part of its cooling media, which ultimately lead to extensive corrosion of the embedded reinforcement throughout the entire structure.

As part of the repair procedure, a CP system was recommended to eliminate any future needs of major repairs that would require a shutdown of the cooling tower beyond the normal planned outage times for regular maintenance. Due to the amount of chlorides and corrosion activity observed at the rebar depth, galvanic anodes would have been insufficient for providing corrosion protection. Instead, an ICCP system was selected. However, due to a planned expansion to the cooling tower capacity in the near future, two out of the four basin walls were omitted from the ICCP system implementation and only concrete repair was performed on those walls. Upon completion of the repair and the CP system installation, the ICCP system was commissioned, operated, and maintained until the expansion to the cooling tower was needed.

By the time the expansion phase was underway, seven years had passed and both the north and south wall showed significant signs of delamination, surface cracking, adhesion failure, and coating failure due to corrosion induced damage (areas without ICCP). In contrast, the east and west walls where the ICCP system was operating showed no signs of corrosion or physical deterioration. The effect of having a CP system extend the repair life of the walls was evident, and the savings in not having to do any repair on the same walls seven years later offset the cost of installing an ICCP system during the previous repair cycle. Worth noting is that the system will continue to protect the walls for at least 20 more years with little to no maintenance required.

The benefit of having an ICCP system protecting the structure from deterioration saved the owner from having to repetitively perform repairs of the walls of the cooling tower basin.

Table 2 - Cost Comparison: Concrete Repair and ICCP Over 8 Year Period

Wall Section	Total Surface Area	2008 Repaired Area (Percentage)	2016 Repaired Area (Percentage)	ICCP Cost in 2008 compared to Concrete Repair Cost in 2016
North	371 ft^2	103 ft^2– (28%)	82 ft^2 – (22%)	70%
South	371 ft^2	126 ft^2 – (33%)	107 ft^2 – (28%)	54%
East	3416 ft^2	1093 ft^2 – (32%)	0	N/A
West	3416 ft^2	1124 ft^2 – (32%)	0	N/A

Note: In 2016 no concrete repairs were needed on the east and west walls, hence ICCP Cost compared to Repair Cost in 2016 is not applicable.

The client understood the financial and operational benefits and had an ICCP system installed on the remaining north and south wall. The overall system capacity was increased to accommodate the new section of the cooling tower basin. A simple firmware expansion enabled overall control from a single main control unit to both the existing and new sections of the ICCP system. As part of the design process, the ICCP system was divided into eight zones that allow tailored CP for each section of the basin according to its exposure and current requirements.

The performance of any CP system can be evaluated using NACE CP standards which are dictated by the environment in which the structure is located and which differ if the structure is buried or atmospherically exposed. For this ICCP system, a 100mV shift depolarization criteria was used to determine the effectiveness of the system in achieving corrosion protection.

The below table shows the depolarization shifts achieved for March 2017. Results show both existing and new build sections performing very well in terms of the desired criteria.

Table 3 - Depolarization Results March 2017

	R1 mV	R2 mV	R3 mV	R4 mV	Zone	R1 mV	R2 mV	R3 mV	R4 mV
Zone 1	168	115	187	98	**Zone 5**	165	157	150	180
Zone 2	111	123	122	119	**Zone 6**	138	155	148	91
Zone 3	132	131	110	175	**Zone 7**	156	180		
Zone 4	108	98	111	185	**Zone 8**	205	129	203	175

Note: Zones 1 to 5 are the existing structure; Zones 6 to 8 are the new build sections

The above example, along with many others, demonstrate that ICCP systems are capable of providing a significant service-life extension for reinforced concrete structures. When choosing the correct system sizing, the owner's service-life extension expectations must be established, as well as the structure's point within its lifecycle. In order to achieve the most suitable system design, the designer must be aware of various parameters such as construction details, construction materials, contamination levels, anode output, steel protective current requirements, system operations, and distribution logistics. Therefore, an in-depth analysis of the structure needs to be carried out before designing a system, preferably by a qualified team with experience in corrosion and material durability issues as well as an understanding of the technologies available for repair.

The success of such systems after installation is based on on-going monitoring by qualified professionals. A life-cycle cost for the system types, compared to traditional repairs, illustrates the value of higher one-time costs for long-term corrosion protection.