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Service Life of Reinforced Concrete Infrastructure in Marine Environments

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Abstract

Reinforced Concrete (RC) is one of the most widely used man-made building materials, even in aggressive conditions. The marine environment is one such place with aggressive conditions, where reinforced concrete is widely used.

The Service Life of a structure can be described as the amount of time for which the structure can carry the service loads imposed upon it without failure. Service life of RC infrastructure is determined by whichever environmental or loading effect most significantly contributes to the structural failure of RC. In marine areas, this effect is deterioration due to reinforcement corrosion, caused by chloride ingress.

Chloride-induced corrosion has many causes, including concrete mix design, construction quality, initial concrete condition, and the surrounding environment.

RC structures constructed from non-reactive dolomite aggregates have enhanced durability against corrosion. Cracks occur in most RC structures at the start of its service life. These cracks readily allow chloride ingress and thus reduce the service life of the RC. The exposure conditions and environment affect the aggressiveness of chloride-induced corrosion in an RC structure determine. These effects have complex causes and interactions and should be considered holistically.

In marine environments an integral part of increasing service life involves preventing and mitigating the adverse effects of chloride-induced corrosion. Ways in which this can be achieved include: including mineral admixtures in concrete mix, using protective coatings on concrete surfaces, monitoring the condition of RC elements, suitable concrete design and adequate construction quality.

Mineral admixtures are used to improve the durability of RC by chemically and physically improving concrete properties. Surface coatings are used on new and repaired RC surfaces in order to preserve initial alkaline environment of the concrete, stop electrolytic processes, and create a surface barrier to control the ingress of aggressive substances. Sensors and models are often used as part of an on-going monitoring system. This helps to ensure cost-effective maintenance and repair. A systematic quality control program ensures concrete reaches the required strengths while proactively managing corrosion risks due to poor construction quality.

It can be seen that a holistic view of the considerations (and mitigation measures) related to chloride-induced corrosion is important in order to ensure an acceptable service life at the design and maintenance stages.
Keywords: Concrete, Marin infrastructure

1. Introduction

Reinforced Concrete (RC) is one of the most widely used man-made building materials. This is due to its versatility and relatively low cost (Shi *et al.* 2012: 125).

Costa & Appleton (2002: 169) state that concrete has been proven as a reliable structural material with very good durability and performance when properly used. Shi *et al*, (2012: 126) agree, adding that concrete has become the preferred material for constructing structures exposed to aggressive conditions.

The marine environment is one such place with aggressive conditions, where reinforced concrete is widely used for in construction (Moradllo *et al.* 2012: 195)

For Costa & Appleton (2002: 169), “experience shows that the corrosion of the reinforcement is the main cause of structural concrete deterioration”. In marine environments chloride-induced rebar corrosion is the main form of environmental attack to RC; and can lead to reduced strength and serviceability in structures. (Shi *et al.* 2012: 126).

This paper will begin by discussing concept of Service Life in order to develop an understanding of which factors will affect the service life of RC infrastructure. The main consideration for service life of RC structures in marine environments will then be highlighted. The paper will then examine what contributes to this key service life consideration, before discussing ways to increase service life. The paper will then conclude with a short summary of key points.

2. Service Life

2.1 What is service life?

The Service Life of a structure can be described as the amount of time for which the structure can carry the service loads imposed upon it without failure. In other words, anything that causes the structure to become unable to bear service loads will reduce its service life.

For most RC infrastructure the main causes of reduced service life are:

- Loads/ loading cases which were not designed for e.g. higher than expected service loads, emergency loads.
- Deterioration of structural RC members

2.2 What determines service life in marine environments?

Service life of RC infrastructure is determined by whichever environmental or loading effect most significantly contributes to the structural failure of RC. In marine areas, this effect is deterioration due to reinforcement corrosion, caused by chloride ingress into RC (Melchers & Li 2009: 1068). Moradllo *et al.* (2012: 198) considers Corrosion due to the salinity of marine environments very hazardous to reinforced concrete.

In general durability design, the limit state of chloride-induced corrosion occurs when the induced chloride amount exceeds the critical chloride content at the location of the embedded steel bar (Kwon et al.; 2008)

Figure 1: 25mm reinforcement bars totally corroded (Costa & Appleton; 2002).

Costa & Appleton (2002: 179) note that corrosion of the reinforcement in RC can cause loss of both reinforcement cross-section (as much as 0.5mm/year) and concrete cross section. Therefore, if un-checked, corrosion can lead to reduction in bearing capacity and thus a reduction in the service life of RC. Figure 1 (page 2-1) shows 25 mm reinforcement bars, which have lost their entire cross section.

3. Causes of Chloride-Induced Corrosion

Chloride-induced corrosion has many causes, including:

- Concrete mix design
- Construction Quality

Initial concrete condition
Exposure conditions and environment

3.1. Concrete Mix Design

The following aspects of concrete mix design affect the service life of RC:

Aggregate choice
w/c ratio
Use of admixtures e.g. fly ash, slag

3.1.1 Aggregate Choice

"…there are a number of cases for which chloride contents were found to be very high yet there was little or no evidence of corrosion initiation… … a contributing factor is … a trend namely that elevated levels of calcareous material in the concrete mix may be linked to enhanced durability of reinforcement against corrosion." (Melchers & Li 2009: 1075).

Melchers & Li (2009: 1075) note that the time period to the commencement of active corrosion was less than 20 years for most structures. However, for reinforced concrete structures constructed from non-reactive dolomite aggregates or with blast furnace cement Melchers & Li (2009: 1075) found it to range from 17 years to more than 60 years (more than 30 years in most cases).

3.1.2 Water Cement (w/c) Ratio

For Castro *et al.* (2001: 536), the concrete's W/C ratio is a determining factor of the degree and duration of chloride saturation in RC. Chloride saturation may not occur even with high chloride concentrations if the environment is stable and concrete is of very good quality. This occurs because an increase in W/C ratio will result in an increase in the chloride diffusion rate and increase the corrosion rate.

3.1.3 Use of Admixtures

See section 4.1

3.1.3 Use of Admixtures

3.2. Construction Quality

Poor construction quality can result in defects such as honeycombing, low cover, and plastic settlement cracks; all of which increase the possibility and rate of rebar corrosion (Beushausen; 2013). For this reason Vu & Stewart (2000: 328) state that the risk of failure is significantly higher in structures where poor workmanship is evident.

3.2.1 Case Study: Arch Bridge

This case study was conducted by Costa & Appleton (2002: 177-79) on a reinforced concrete (RC) arch bridge located near the estuary of River Sado in Portugal. The bridge was 35 years old, and had not been maintained prior to the study. It was determined that the bridge was located in a sea spray zone (no direct contact with seawater). Figure 2

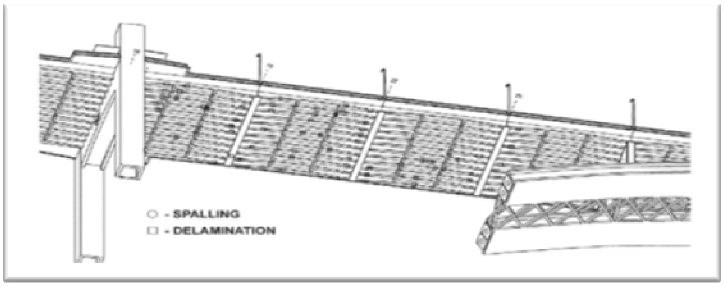


Figure 2: Locations of spalling and delamination under bridge deck (Costa and Appleton; 2002).

(below) shows the results of a visual inspection of the underside of bridge deck
Costa & Appleton (2002: 177-79) noted the following:

Low-quality construction joints and honeycombing were noted frequently
Thickness of concrete cover was very inconstant
A significant area of beams had cover less than 20mm

Regarding the corrosion rate, Costa & Appleton (2002: 177-79) found that "corrosion rate measurements… …show that on the areas without defects the reinforcement is in a passive condition, values below1 μm/year were measured. On a poorly made construction joint a value of 7 μm/year was measured.

Andrade *et al.* (1993: 453-64) show that a loss of reinforcement bar cross-section as small as 20 μm may be enough to crack the concrete cover. When the radius loss of the bar is about 100 μm a crack width of 0.3–0.4 mm is reached. These cracks allow increased chloride ingress, further accelerating corrosion.

Figures 3-4 (below) show other kinds of deterioration found on the bridge, related to ungrouted prestressing ducts and low cover.

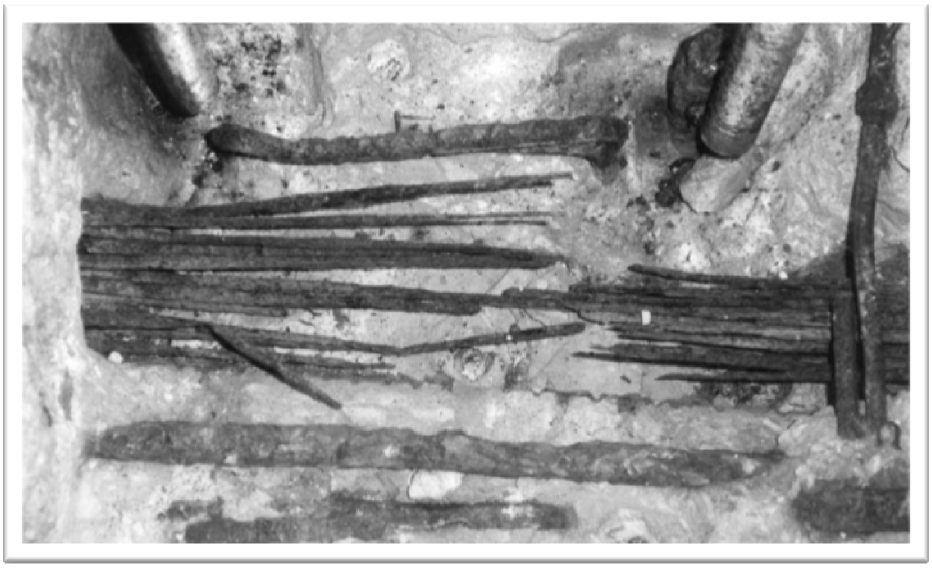


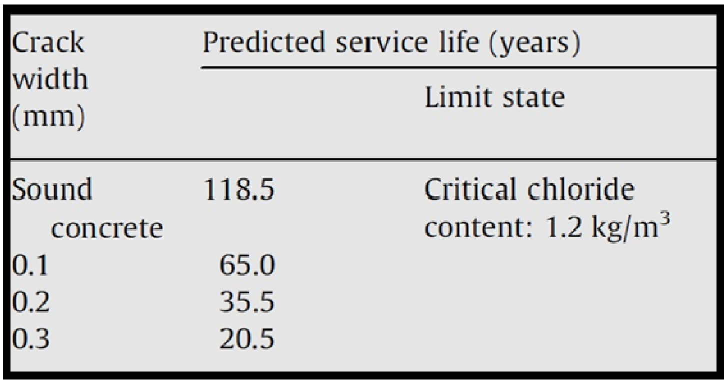
Figure 3: Corrosion of prestressing steel in un-grouted ducts (Costa and Appleton; 2002).

Figure 4: Concrete spalling in a low cover zone (Costa and Appleton; 2002).

3.3 *Initial Concrete Condition*

Cracks due to material characteristics (e.g. hydration heat and drying shrinkage) occur in most RC structure at the start of its service life (Beushausen 2013). These cracks can aid chloride ingress and thus reduce the service life of the RC (Kwon et al.; 2008). Table 1 shows how dramatically the service life of a RC structure is affected by an increase in crack width.

Table1: Predicted service life corresponding to crack width (Kwon et al.; 2008)



Crack width (mm)	Predicted service life (years)	
		Limit state
Sound concrete	118.5	Critical chloride content: 1.2 kg/m^3
0.1	65.0	
0.2	35.5	
0.3	20.5	

3.4 Exposure Conditions and Environment

The deterioration rate observed in already defective structures are determined by the exposure conditions of the various elements of the structure (Costa & Appleton; 2002).

Understanding the exposure conditions and environment of an RC structure is key in determining the aggressiveness of chloride-induced corrosion.

The following should be considered:
Zone e.g. submerged, tidal, and spray zones (when very close the ocean
Proximity to the ocean (when in a coastal area)
Climate

3.4.1 Zone

There are three zones of concern in the marine environment, namely:

1. Submerged zone
2. Tidal zone
3. Spray zone

Submerged Zone

The submerged zone is where the RC member is ere can be no normal red chloride-induced corrosion in this zone as the corrosion reaction requires oxygen which is not available in high enough quantities this zone. For this reason a different electrolytic reaction takes place in the submerged zone. The result is a black corrosion product, characteristic of low-oxygen (from H_2O) environments.

Unlike common rust, this “black rust” is not a voluminous corrosion product. Therefore there is no visible spalling or delamination caused by pressure due to the rust expanding against the concrete. Thus the corrosion damage is only visible when catastrophic structural failure of the RC member occurs. However the corrosion rate in the submerged zone is in general much lower than in environments with normal oxygen levels.

Tidal Zone

RC elements in the tidal zone undergo cycles of wetting and drying, as the tide comes in and goes out. These cycles have the effect of introducing chlorides into the concrete (when the tide comes in), and then allowing oxygen to enter (as the tide goes out and the RC dries). This cycle of wet and dry creates the perfect conditions for corrosion.

For this reason, the highest deterioration rates usually occur in this zone. (Costa & Appleton 2002: 179) note that corrosion rates in excess of 0.5mm/year are possible in the tidal zone. Moradllo *et al.* (2012: 200) add that the wet-dry cycles, and cyclic wave impacts characteristic of the tidal zone are able to deteriorate thin cementious surface coatings in a matter of months. (See section 4.2 for more on coatings)

Spray Zone:

Sea spray is a transport mechanism by which chloride ions from sea water are carried by the wind, and accumulate on the concrete surface

This happens in coastal areas, where the RC is not in direct contact with the sea water (Vu & Stewart; 2000: 317). Because winds have been known to carry sea spray as much as 3 km inland (Neville 1995: 63-70), it is possible to be within the spray zone while at a distance from the sea. This can make the correct identification of environmental conditions difficult.

3.4.2 Proximity to the Ocean

Figure 5 (below) indicates a direct correlation between an RC element's proximity to the sea and its probability of failure with time.

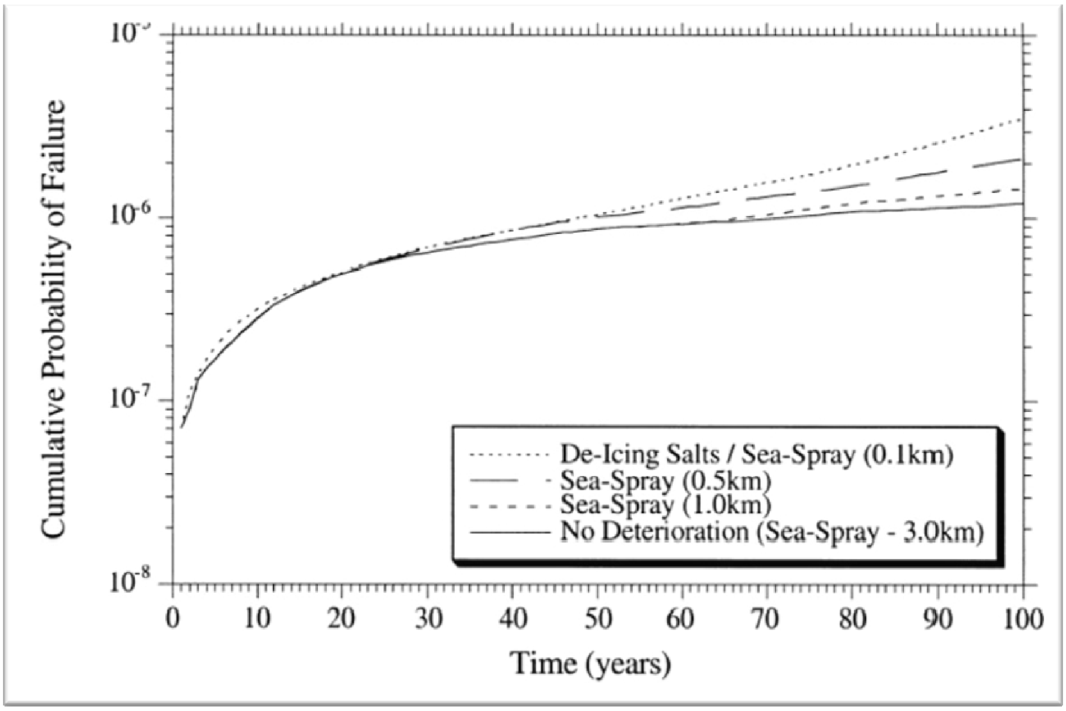


Figure 5: Probability of failure due to sea proximity (Vu & Stewart; 2000).

Sea proximity affects how much sea spray an RC element receives, and thus the rate of chloride ingress into the element. Berke & Hicks (1992: 207-31) found that "concentration of air-borne chlorides on the surface of a concrete member is dependent on environmental conditions and… …distance from the coastline". Furthermore, empirical data reveals a clear correlation between chloride concentration inside the RC and the distance to the sea. This correlation held as far into the concrete as the reinforcement depth (Castro *et al.* 2001: 536).

3.4.3 Climate

The climate an RC structure is in can have various effects on the RC element's durability as will be discussed. Furthermore, aside from environmental effects intrinsic to each specific climate, the temperature within the concrete, the temperature at depth in the RC will be directly affected.

Climate Effects

Corvo *et al.* (2008: 220–230) states that a very humid climate can cause chloride ions to leach quickly, diminishing their effect on the acceleration of corrosion rate

Corvo *et al.* (2005: 883–892) reports that "the acceleration rate caused by chloride ions on atmospheric corrosion of steel depends on the characteristics of rain regime. For a place having high amount and time of rain, a lower acceleration on corrosion rate should be expected for a given chloride deposition rate". As a possible explanation, Corvo *et al.* (2008: 229) proposes the washing effect of rain, mentioning that the increase in airborne salinity during dry season must be taken into account.

Temperature

"Temperature has a significant effect on the corrosion rate of steel in concrete, as with other chemical and electrochemical reactions" (Liu & Weyers 1997: 365).

Liu & Weyers (1997: 374) show that generally, an increase in temperature within the RC element will result in an increase in the rate of corrosion. Figure 6 (page 3-7) shows the effect of increasing temperature on chloride corrosion rates in concrete.

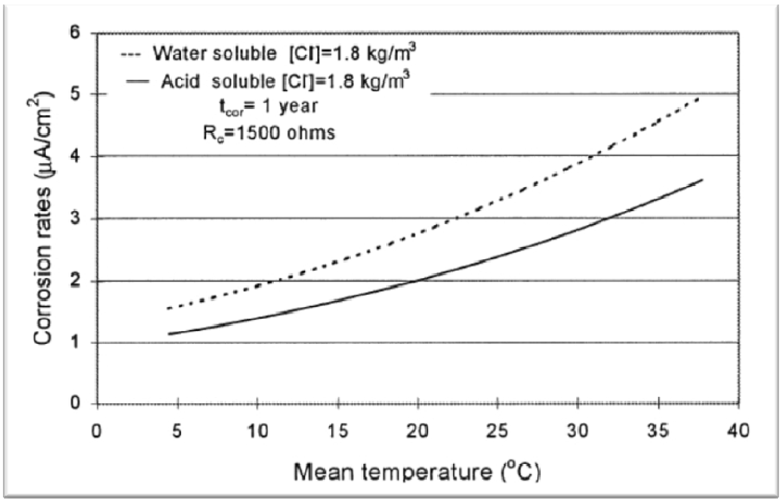


Figure 6: Effect of temperature at depth within concrete on concrete corrosion rate (Liu & Weyers 1997: 374).

However, Liu & Weyers (1997: 374) mention that changes of temperature in concrete affect other parameters (e.g. resistance of concrete, oxygen diffusion rate), which in turn also affect corrosion rate. Interactions between these factors make determining the overall effect of temperature on corrosion rate complex.

4. Increasing Service Life

In marine environments an integral part of increasing service life involves preventing and mitigating the adverse effects of chloride-induced corrosion.

The following are some of the ways this can be achieved:
Use of mineral admixtures in concrete mix
Protective coatings on concrete surface
Monitoring the condition of RC elements
Suitable concrete design
Adequate construction quality

When applied during the design and construction phases, these measures will prevent corrosion from starting. If applied after corrosion has already started, these measures will serve to mitigate corrosion. However, the degree of effectiveness will depend on how suitable the measure is, as well as whether it is applied before significant deterioration has taken place.

4.1 Mineral Admixtures

"Mineral admixtures, generally pozzolanic materials, are mainly glassy siliceous materials that may contain aluminous compounds" (Hart *et al.* 1999). The reaction of such materials with cement hydration products (calcium hydroxide) and water produces hydration products similar to calcium hydroxide i.e. calcium silicate hydrates (C–S–H):

Pozzolanic material + water + $Ca[OH]_2$ = C—S—H (Shi *et al.* 2012: 126).

When used to supplement cement, materials such as fly ash, silica fume, and slag have generally improve the resistance of concrete to chloride penetration (Shi *et al.* 2012: 126).

(Melchers & Li; 2009: 1075) found that the use of mineral admixtures was able to extend the initiation time of chloride corrosion from 5 years to as much as 15 years where high quality construction was evident. Kwon *et al.* (2009: 80) explains this, showing that diffusion decreases more rapidly in concrete with mineral admixtures than in Portland Cement (OPC). This is due to improved pore structures (Thomas & Bamforth 1999: 487–95) and more enhanced chloride binding capacity in concretes with mineral admixtures (Lu *et al.* 2002: 323–6).

There are several kinds of mineral admixtures including:

Fly Ash (FA)
Ultra-fine Fly Ash (UFFA)
Silica Flume (SF)
Ground Granulated Blast Furnace Slag (GGBS)
Metakaolin (MK)

4.1.1 Fly Ash (FA)

"Fly ash (FA) is a by-product of coal combustion in the generation of electricity, i.e., a finely segregated residue captured from the flue gas at coal-fired power plants" (Shi *et al.* 2012: 128).

The addition FA in concrete is an effective way to mitigate chloride-induced corrosion of RC, as it has been found to reduce chloride permeability (Shi *et al.* 2012: 128).

4.1.2 Ultra-fine Fly Ash (UFFA)

Including UFFA in the concrete mix is known to reduce free shrinkage, increase cracking age, and decreased creep (Shi *et al.* 2012: 128). This reduces the likelihood of chloride ingress via early age cracks.

4.1.3 Silica Flume (SF)

"Silica fume (SF) is typically a by-product of manufacturing silicon and ferrosilicon alloys… …a finely segregated residue captured from the oxidized vapour on top of the electric arc furnaces" (Shi *et al.* 2012: 128).

SF is known by Shi *et al.* (2012: 128) to considerably reduce the risk of rebar corrosion in RC by lowering its permeability. This is achieved by chemically and physically refining the concrete's microstructure.

4.1.4 Ground Granulated Blast Furnace Slag (GGBS)

Shi *et al.* (2012: 129) defines GGBS as "a by-product of making iron and steel, i.e., a fine powder grounded from the glassy, granular material that forms when molten iron blast furnace slag is air quenched with water or steam"

Shi *et al.* (2012: 129) attributed the following durability advantages to GGBS:

Improved the pore structure in concrete,
Increased chloride-binding ability
Reduced chloride diffusion
Increased concrete resistivity

As a result of the advantages mentioned above, the corrosion initiation time of steel in RC can be more than 3 times as long when 50% of cement is replaced with GGBS (Al-Gahtani *et al.* 1993: 223–33).

4.1.5 Metakaolin (MK)

"Metakaolin (MK) is a material obtained by calcining clay mineral kaolinite between 500–800 °C… …so that it loses water through dehydroxilization (i.e., removal of chemically bonded hydroxyl ions)."

The replacement 10% or 20% (by weight of cement) with MK greatly reduces chloride permeability of concrete, by decreasing average pore size while increasing uniformity in the of pore sizes (Badogiannis & Tsivilis 2009: 128-33). This has an associated decrease in water permeability, and thus, also a decrease in conductivity (Shi *et al.* 2012: 129).

4.2 Protective Coatings

Moradllo et al (2012: 198) state that “Surface protection method is one of the main means which is applied to new or repaired structures placed in corrosive environment and many researchers have reported efficacy of this method in limitation of chloride penetration and hence, enhancing resistance to chloride induced corrosion of embedded reinforcement”. Table 2 (page 4-4) lists the various coating types.

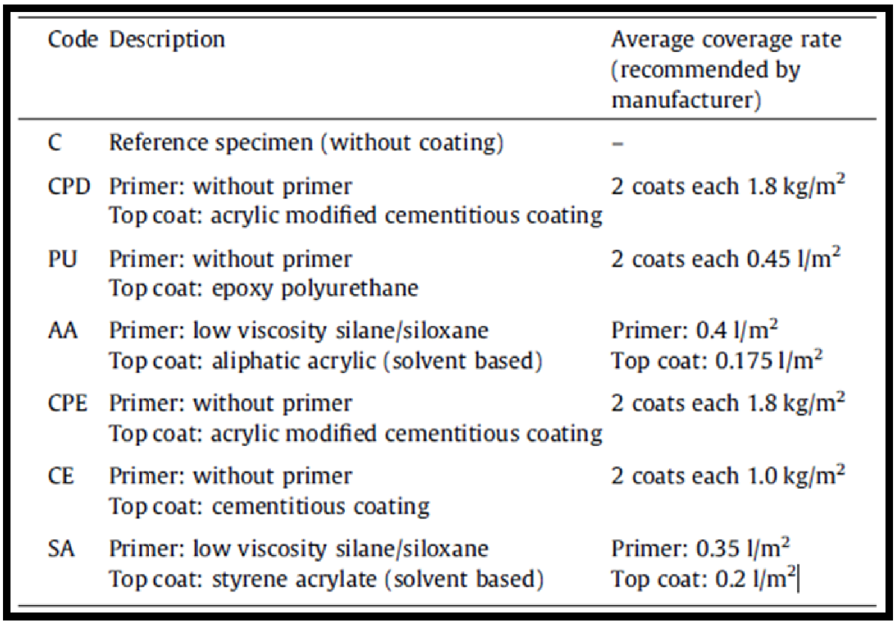
According to Almusallam *et al.* (2002: 487‑94), surface coatings must possess certain engineering and durability properties in order to form a suitable barrier on the surface of concrete:

1. Water impermeability;
2. Water vapour impermeability
3. Thermal stability
4. Adequate adhesion
5. Crack-bridging ability
6. Adequate elasticity.

The abovementioned properties are utilised to:

preserve initial alkaline environment of the concrete
Stopping the anodic process where the reinforcement is corroding
Creating a surface barrier to control the ingress of further aggressive substances
Limiting moisture content of the concrete by excluding external water and water vapour, which allows concrete to dry out. This raises concrete resistivity, and the electrolytic process of the corrosion mechanism is controlled (Appleton & Costa 2002: 179), (Moradllo et al 2012: 198), (Almusallam *et al.* 2002: 487‑94).

Table 2: Protective coatings and recommended coverage



Code	Description	Average coverage rate (recommended by manufacturer)
C	Reference specimen (without coating)	–
CPD	Primer: without primer Top coat: acrylic modified cementitious coating	2 coats each 1.8 kg/m^2
PU	Primer: without primer Top coat: epoxy polyurethane	2 coats each 0.45 l/m^2
AA	Primer: low viscosity silane/siloxane Top coat: aliphatic acrylic (solvent based)	Primer: 0.4 l/m^2 Top coat: 0.175 l/m^2
CPE	Primer: without primer Top coat: acrylic modified cementitious coating	2 coats each 1.8 kg/m^2
CE	Primer: without primer Top coat: cementitious coating	2 coats each 1.0 kg/m^2
SA	Primer: low viscosity silane/siloxane Top coat: styrene acrylate (solvent based)	Primer: 0.35 l/m^2 Top coat: 0.2 l/m^2

Moradllo *et al*. (2012: 202) found that Aliphatic Acrylic (AA) and Epoxy Polyurethane (PU) coatings are best for preventing chloride ingress. However, Moradllo *et al*. (2012: 200) mentions that in order for surface coatings to remain effective they must be reapplied before they have deteriorated.

4.3 Corrosion Monitoring

Sensors and models are often used as part of an on-going monitoring system. This helps to ensure that maintenance is done economically and at the optimal time.

4.3.1 Sensors:

The following types of sensors are used to monitor corrosion in RC in various ways (Costa & Appleton; 2002: 173):

Reference electrodes to monitor electrochemical potential of reinforcement
Macrocell sensors to monitor the onset of corrosion
Temperature sensors
Resistivity sensors.

Sensors are often installed during construction or after repair for on-going monitoring (Costa & Appleton; 2002: 173).

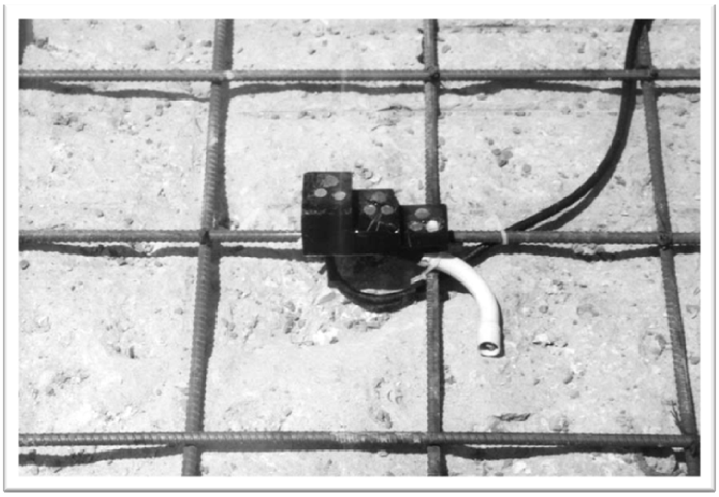


Figure 7: Corrosion sensor installed during repair (Costa & Appleton; 2002).

4.3.2 Service life models:

The main advantage of service life models is that they allow cost-effective decisions to be made about the timing of repairs and replacement. A well-developed model should clearly indicate which corrosion control strategies are most effective. However, service life of reinforced concrete can be very difficult to predict or model in the field environment, as it depends on mechanical properties of the concrete (Shi et al.; 2012).

4.4 Concrete Design

Concrete design must consider durability performance criteria as well as the surrounding environment to protect RC structures against aggressive chloride corrosion. Vu & Stewart (2000: 328) find it clear that lower standard durability specifications will result in an increase in probability of failure, by several orders of magnitude.

The cost of maintaining, repairing or replacing degraded existing structures can be very large (Costa & Appleton 200:179). Thus, Vu & Stewart (2000: 328) agree that: "…there is obviously a strong financial incentive for the optimal allocation of resources, not only for repair and rehabilitation strategies, but also for initial design…"

In the context of a marine environment, a suitable reinforced concrete design is one which considers (among others) the issues mentioned in Section 3 and Section 4 of this paper.

4.5 Construction Quality Control

Poor construction quality (workmanship) usually results in a dramatic reduction in concrete compressive strength (Vu & Stewart 2000: 328). This is due to an increase in the W/C ratio associated with below-standard workmanship when casting the RC. Vu & Stewart (2000: 328) believe this loss in strength can have a worse effect on structural reliability than reduced cover depth.

Costa & Appleton (2002: 179) note that both the financial and environmental costs of repair are high. To avoid such costs Costa & Appleton (2002: 179) suggest planning and execution based on sound design and quality workmanship.

A systematic quality control program:

- Ensures concrete reaches the required strengths
- Helps to manage corrosion risks (due to poor construction quality) pro-actively.

It can be seen that a good quality control program will greatly reduce the risk of cracking and rebar corrosion in concrete (Shi *et al.* 2012: 134).

5. Conclusion

It can be concluded that the critical factor in determining service life in marine Environments is chloride-induced corrosion. Chloride-induced corrosion is affected by several factors (including poor design, construction quality, and adverse environmental effects). Therefore a holistic approach is required when understanding each of these considerations, and the interactions between them

In order to prevent rapid deterioration of existing structures, intervention, and on-going monitoring is needed. This is effectively done using sensors to monitor the rate and extent of corrosion. Service life models can give a useful indication of when the RC structure will need maintenance or repair. However, models are only reliable when several applicable environmental and design factors are taken into consideration.

In order to prevent rapid deterioration of future structures, they must be designed to meet durability requirements. There is a need not only to design with durability in mind, but to make it an integral consideration during all aspects of the design process. This is because of the wide range of factors which contribute to deterioration of RC structures in this environment.

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