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# Oxygen Availability and Corrosion Propagation in RC Structures in the Marine Environment—Inferences from Field and Laboratory Studies

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**Abstract:** The splash and spray and tidal zones are generally assumed to be the most severe marine exposure environments with respect to steel reinforcement corrosion in concrete structures. However, it has been observed in several aged marine structures along the Southern African coastlines, that there is usually relatively insignificant reinforcement corrosion damage in the tidal zone, despite very high (above-threshold) chloride contents. To develop a full understanding of the severity of marine exposure conditions with regard to the actual deterioration, it is imperative that other factors that directly affect corrosion, such as oxygen availability at the steel surface (which is influenced by concrete quality, cover thickness and moisture condition), are carefully considered. The laboratory experimental work in the study presented in this paper comprised of different cover depths (10, 20 and 30 mm) and w/b ratios (0.5 and 0.8) and simulated marine tidal, splash and submerged environments. The results show that for any give exposure environment, the relative influence of each of the various factors considered should be considered in conjunction with the other factors; this finding can be generalized to include all relevant factors that can affect corrosion in a given exposure environment including ambient temperature. For example, a cover depth of 30 mm in the tidal zone with a simulated intertidal duration of 6 h effectively resulted in similar corrosion behavior to that in the submerged zone. The paper concludes that engineers should consider these factors when applying standard exposure classes in the design for durability of marine structures.

**Keywords:** marine exposure classes; tidal zone; chloride ingress; reinforcement corrosion

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## 1. Introduction

Premature deterioration of reinforced concrete (RC) structures, particularly in the marine environment, has become a pervasive issue worldwide. Depassivation of steel reinforcement leading to corrosion in concrete structures exposed to marine environments occurs as a result of the penetration of chloride ions through the concrete cover, which initiate corrosion of the embedded reinforcing steel. In the majority of cases, the steel corrosion progresses to the propagation stage, which results in the premature deterioration of the RC structures and consequently in high maintenance, repair and rehabilitation costs.

The Eurocode document EN 206 [1] is a framework that was developed to guide and support engineers in the transition toward a performance-based durability design of RC structures in aggressive environments and distinguishes three marine exposure zones to predict the severity of potential steel corrosion. The exposure zones are classified in order of increasing aggressiveness as (i) XS1—structures near the coast (airborne chloride exposure), (ii) XS2—submerged structures and (iii) XS3—structures in the tidal and splash and spray zones. This classification is based on the expected rate of deterioration due to chloride-induced steel corrosion, with XS3 classified as the most aggressive exposure zone.

However, the classification does not, to a large extent, take into account salient factors, such as, among others, the effect of temperature and relative humidity, wind intensity, salinity of the sea water, duration of wetting–drying cycles and time of wetting due to tides and type and amount of suspended solid particles in sea water [2]. Otieno and Thomas [2] posit that an appropriate combination of these factors should be considered when characterizing a marine exposure environment in a performance-based service life design process.

The study presented in this paper focused on the durability performance with respect to steel corrosion of RC structures in the marine tidal zone. The paper is based partly on the findings of condition assessments of a number of aged in-service RC structures (ca. 45–65 years) along the east and west coasts of Southern Africa, which indicate that sections of these structures in the tidal zone—classified as XS3 according to EN 206—show minimal signs of steel corrosion-induced degradation [3], and partly on laboratory experiments. This is contrary to the expectation of, according to EN 206, a relatively higher degree of deterioration of these structures in sections exposed to the tidal zone than those in the other exposure environments. These findings corroborate the recommendation by Otieno and Thomas [2] and clearly indicate that the EN 206 classifications of the aggressivity of marine exposure environments and the associated recommendations on durability specifications can be overly conservative. There is therefore need for careful assessment of each marine exposure environment and hence considered decisions and judgments in the design, specification and condition assessment of RC structures in marine environments.

This paper aims to demonstrate the discrepancy that can manifest if, for example, the marine tidal and splash and spray zones are considered as being equally aggressive during either design and specification or condition assessment. Laboratory experiments were conducted in this study to test this school of thought. Arguably, the most significant implication of the findings of the study presented in this paper is that it will challenge engineers to pay more attention to the performance and/or deterioration of in-service RC structures in the marine environment during condition assessments. Subsequently, this will lead to more sustainable and functional repair and maintenance decisions and actions. In addition, the study findings can help in the refining of the characterization of the aggressivity of the marine exposure environment for improved designs. The findings reported here are applicable to RC infrastructure exposed to tidal and submerged marine exposure environments.

*Mechanism of Steel Corrosion in Concrete*

Steel corrosion in concrete is triggered by the ingress of deleterious substances through the concrete cover. In the case of chloride-induced corrosion in RC structures in the marine environment (illustrated in Figure 1), it is initiated once a critical chloride concentration is accumulated at the steel level to cause passivity breakdown, rendering the steel liable to further corrosion. In the presence of corrosion-sustaining species (moisture and oxygen), the corrosion process progresses to the propagation stage that is accompanied with, among other effects, a loss in the steel cross-sectional area that directly affects structural integrity [4].

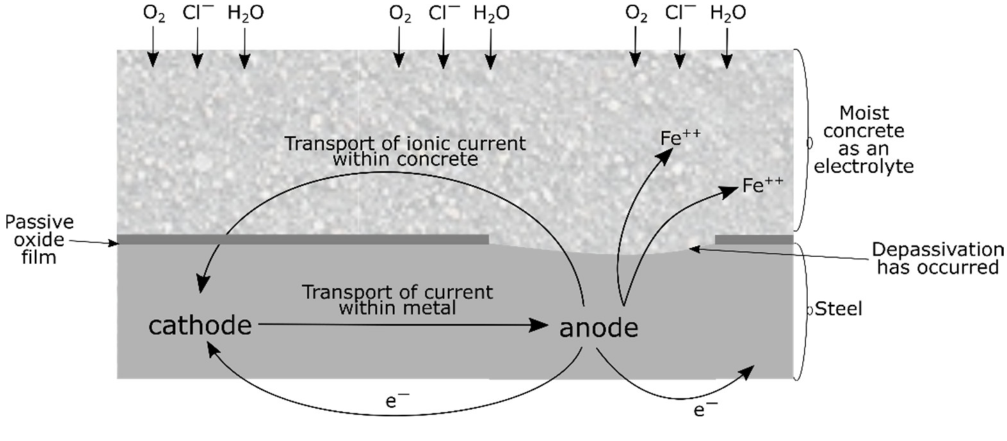


**Figure 1.** Schematic of chloride-induced steel corrosion in concrete.

The rate of steel corrosion, which depicts the rate of dissolution of steel, is affected by a combination of factors, some inter-related, including the penetrability (quality and condition) of the concrete cover, temperature and relative humidity and resistivity of the concrete [5]. These factors, or a combination thereof, determine the corrosion rate-controlling phenomenon viz., anodic control, cathodic control or resistivity control of the corrosion rate, respectively [4,6].

## 2. Marine Exposure Environments

The marine exposure environment is typically classified into three main zones viz., the airborne, splash and spray, tidal and submerged exposure zones. Each zone is characterized by different environmental conditions, and thus chloride penetration through concrete is driven by different transport mechanisms as shown in Figure 2. In the submerged zone, chloride ions penetrate the concrete cover primarily by diffusion, while chlorides in the tidal and splash and spray zones predominantly penetrate the concrete cover by a combination of both capillary absorption and diffusion processes. Partially submerged RC elements may also experience wick action when dissolved chloride ions are transported by capillary suction from the submerged regions of the element to the dry concrete surface in nonsubmerged regions, where evaporation of the surface moisture leads to an increase in the concentration of surface chloride ions. Wick action exacerbates chloride-induced corrosion in partially submerged RC structures provided sufficient dissolved oxygen is available to sustain the cathodic corrosion reactions, which is most notably the case in structures or parts of structures exposed to the splash and spray zone or airborne chloride exposure [3].

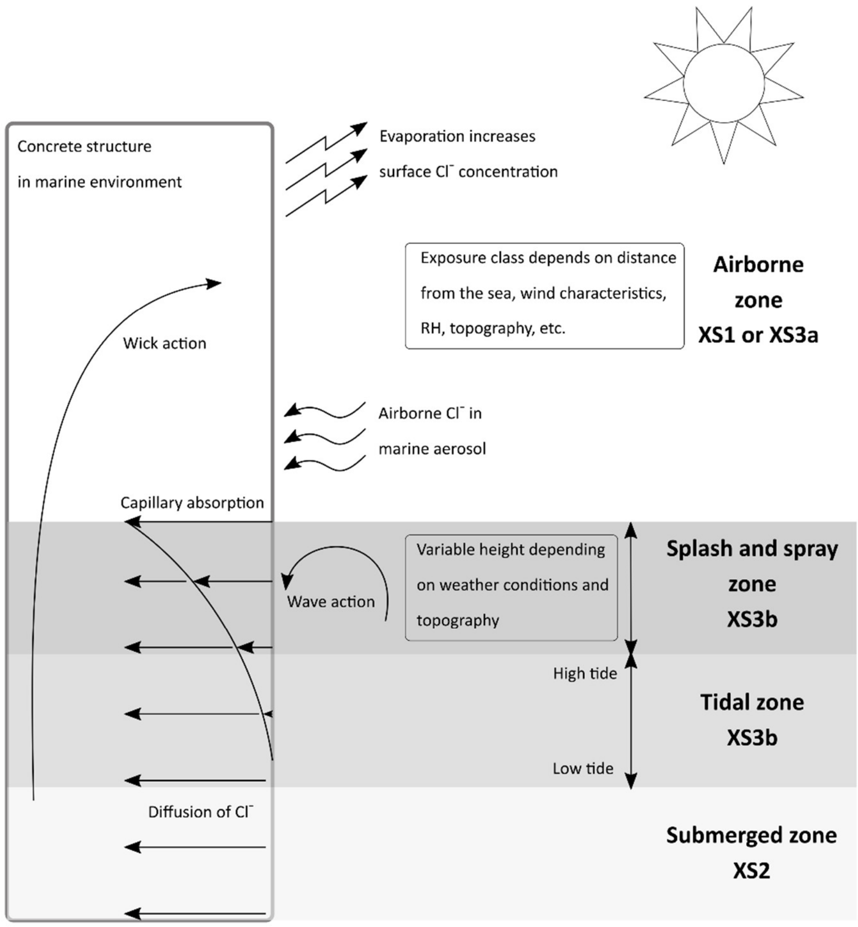


**Figure 2.** Marine exposure environment classification and corresponding transport mechanisms for concrete structures (extracted from Beushausen et al. [7]).

The following sections will only discuss the submerged, tidal and splash and spray zones, which are the focus of this paper.

### 2.1. Splash and Spray Zone

The splash and spray zone (sometimes termed the splash zone) is located above the high-tide level where wave action causes moisture to splash onto the concrete surface, as shown in Figure 2. The risk of reinforcement corrosion is generally considered to be highest in the splash and spray zone [8]. Both the chloride ion penetration and the subsequent reinforcement corrosion are relatively fast within this region. The penetration of chlorides in the splash and spray zone occurs predominantly by capillary absorption of sea water and is exacerbated by the partial drying of the cover concrete resulting in wicking action. This generally leads to greater chloride ion concentrations in this zone than those experienced in the tidal and submerged zones. A combination of the availability of both chloride ions and oxygen results in high reinforcement corrosion rates in the splash and spray zone.

Typical reinforcement corrosion damage observed on concrete structures in Southern Africa in the splash and spray zone is shown in Figures 3 and 4. Figure 3 shows a concrete jetty, where severe reinforcement corrosion damage was observed on the downstand beams of the deck. In addition, this structure experienced significant steel corrosion damage on the piles, but only above the high-water line close to the deck soffit. Similarly, on the structure shown in Figure 4, significant reinforcement corrosion damage was observed on the concrete piles, but only above the high-water line toward the deck soffit. In no instance was any damage observed in the tidal zone, i.e., below the high-water mark. In Figure 4, the top of the barnacles marks the high-water line on the concrete piles. The authors have made similar observations on many other structures along the Southern African west and east coasts.

**Figure 3.** Steel corrosion damage in the splash and spray zone: concrete jetty on the Southern African west coast (age: ca. 50 years).

### 2.2. Submerged Zone

In this zone, RC structures or their elements are permanently submerged and saturated to the reinforcement. When permanently submerged, chloride ions predominantly penetrate the concrete to the steel level by diffusion [8], which is relatively slower than capillary suction in unsaturated concrete [9]. Therefore, lower chloride concentrations can generally be expected in the submerged zone compared to the tidal zone. The degree of concrete saturation in this zone also negatively affects the diffusion of oxygen in concrete by up to 4 orders of magnitude [10]; this has a negative effect on corrosion propagation to the extent that steel corrosion is stifled in the submerged zone [11]. It is noted, however, that severe corrosion may still occur due to macrocell coupling even in submerged conditions [12].


**Figure 4.** Steel corrosion damage on concrete piles above the high-tide line in the splash and spray zone: concrete berth on the Southern African east coast (age: ca. 50 years).

### *2.3. Tidal Zone*

This zone is defined by the depth of the region between high and low tides, which occur twice a day separated by approximately 12 h. However, this frequency is known to vary from season to season and from region to region [13]. The cyclic wetting and drying are not only associated with a heating and cooling effect but are also known to accelerate the initiation and propagation of steel corrosion as it can lead to an increased rate of penetration of species, such as chlorides, in the concrete [9].

When concrete is dry or partially dry, sea water penetrates the concrete mainly through capillary suction until saturation or until the tide falls. If the surrounding environment is dry after the tide falls, moisture evaporates from the pores of the concrete, leaving behind crystalline salt precipitate. When the concrete is wetted again during high tide, the salt crystal precipitates dissolve in the sea water, and chloride ions are carried further into the concrete pores. Repeated cycles of wetting and drying drive chlorides deeper into the concrete, and steel corrosion is initiated if a critical chloride concentration is reached at the reinforcing steel.

## 3. Experimental Investigation

As already mentioned, the progression of steel corrosion to and during the corrosion propagation phase is dependent on the availability of corrosion-sustaining species, mainly moisture and oxygen that are to a large extent mutually exclusive. As concrete dries out, its pores become less saturated, and the diffusivity of oxygen is increased. The increase in availability of oxygen is expected to result in increased corrosion rates in the tidal zone relative to those in the submerged zone. Fundamentally, this informs the hypothesis that RC structures exposed to cyclic wetting and drying in the tidal zone have an inherently higher risk of deterioration due to steel corrosion than those in the permanently submerged zone—mainly due to oxygen deficiency. However, an assessment of the durability performance of in-service RC structures along the Southern African coastlines with respect to steel corrosion has shown contrary results.

In an attempt to understand the durability performance of these structures, an empirical study was conducted to test the aforementioned hypothesis. A total of 36 concrete corrosion prisms with dimensions 120 × 122 × 380 mm were made using CEM I 52.5N, with w/b ratios of 0.50 and 0.80. Three cover depths to the stainless steel (grade 316) cathodes of 10, 20 and 30 mm were used to simulate oxygen availability. The specimens were allowed to dry for 2 weeks in a 50% relative humidity (RH) environment, before being sealed with epoxy on the 4 surfaces perpendicular to the exposure surface. The specimens were exposed to simulated marine environments that included submerged, cyclic wetting and drying (tidal zone) and periodic splashing exposure as follows:

(i) submerged exposure: the specimens were permanently saturated with a 5% NaCl solution contained in an in-built reservoir (dam) in the specimens (see Figure 5);
(ii) splash and spray zone: the specimens were sprayed with 5% NaCl solution every second day;
(iii) tidal zone: the specimens were subjected to continuous 12 h cycles consisting of 6 h of wetting with 5% NaCl solution and 6 h of air-drying.

A modified version of the ASTM G109 [14] macrocell corrosion set up shown in Figure 5 was used. The influence of a coupling corrosion circuit in the corrosion set-up was not explicitly considered in this study as this was not expected to be significant taking into account the controlled specimen environmental exposure conditions. In addition, high-grade stainless steel (316) was used to ensure that the cathodes remained passive. The authors are therefore confident that the trends obtained from the study and the conclusions hold. Nevertheless, future investigations will need to assess and quantify the effects of these phenomena, if any.

In order to accelerate the corrosion process, 5% chlorides by weight of cement (as NaCl) were admixed in the concrete used to cast the top half of the prisms where the working electrode was embedded, while the other half of the concrete was chloride-free. The macrocell corrosion current ($i$) was monitored indirectly in each of the specimens by taking weekly voltage ($V$) measurements across a 100 Ω resistor ($R$). Macrocell corrosion current was then determined using Ohm's law $i = VR^{-1}$ [15]. The total integrated corrosion current ($TIC_{corr}$, coulombs) was calculated for each corrosion cell using Equation (1) [14]

$$TIC_j = TIC_{j-1} + \left[ \left( t_j - t_{j-1} \right) \times \frac{(i_j + i_{j-1})}{2} \right], \tag{1}$$

where $t_j$= time in seconds, and $i_j$= macrocell current at time $t_j$ in amps. The total integrated currents were used to infer relationships among all 3 parameters (cover depth, w/b ratio and exposure conditions) and their influence on the corrosion rate. For each concrete mix, three companion concrete specimens were cast to establish moisture profiles in the concretes in the different exposure zones, Figure 6. From these specimens, the relative humidity of the concrete at different cover depths and w/b ratios could be determined for corrosion cells located in the different exposure conditions. A moisture probe was used to measure the relative humidity at the steel level for the various cover depths (10, 20 and 30 mm). Relative humidity readings were taken at 5 different times during the experiment (days 60, 80, 102, 120 and 145).

### 3.1. Comparison of $TIC_{corr}$ in Different Exposure Conditions

A summary of the total integrated macrocell current $TIC_{corr}$ for the specimens exposed to the various exposure environments over a measurement period of 160 days is presented in Figure 7. The specimens in the splash and spray zone showed the highest $TIC_{corr}$. The values recorded for this zone were significantly higher than the 150 C active corrosion threshold with 417 C being the lowest value recorded. When making a comparison of the specimens within the splash and spray zone, it is noted that the $TIC_{corr}$ decreased with an increase in the cover depth. Considering specimens with a w/b ratio of 0.8, the specimen with a cover depth of 10 mm had a $TIC_{corr}$ of 1006 C, whereas the specimens with cover depths of 20 mm and 30 mm had values of 698 C and 484 C, respectively. A similar trend appeared when considering specimens with a w/b ratio of 0.5 in the splash and spray zone. When comparing the $TIC_{corr}$ in specimens with different w/b ratios (given the same cover depth and exposure conditions), the w/b ratio of 0.8 consistently yielded higher $TIC_{corr}$ than a w/b ratio of 0.5.

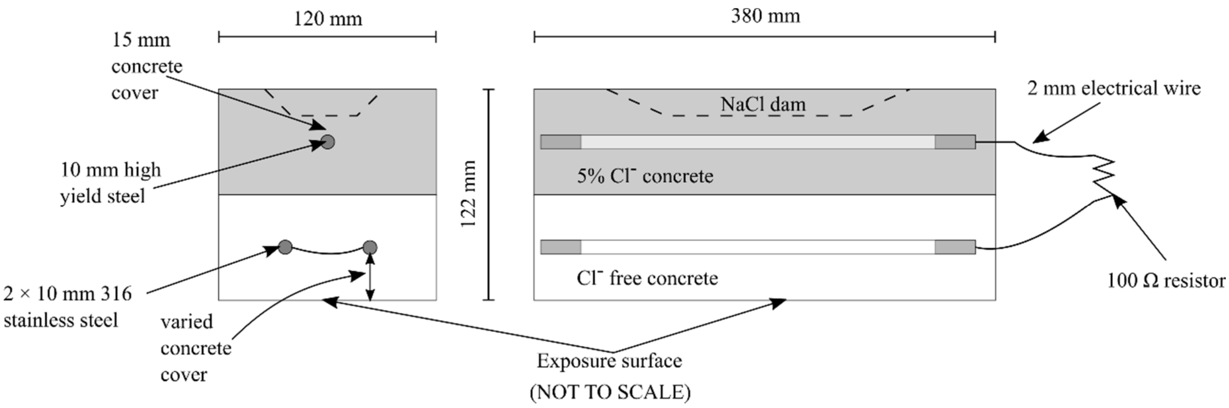


**Figure 5.** Schematic of macrocell corrosion prism.

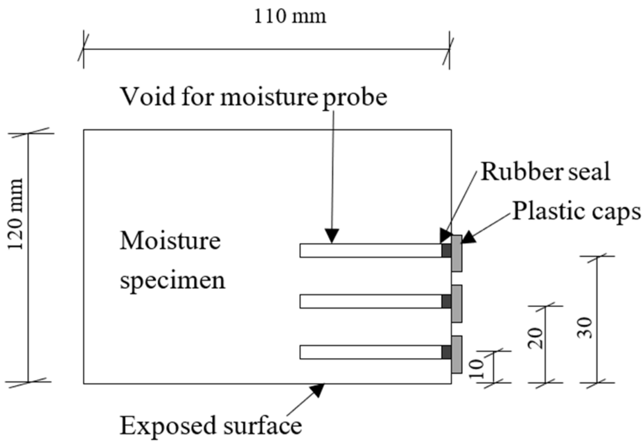


**Figure 6.** Schematic of moisture prism specimen.

The specimens in the submerged zone had the lowest $TIC_{corr}$ overall. All the specimens in this zone had very low $TIC_{corr}$ values over 160 days. The specimens with 10 mm cover depths had slightly higher $TIC_{corr}$ values for both w/b ratios than the other cover depths. The small differences in these $TIC_{corr}$ values may be attributed to general variability in the measurement. This indicates that the cover depth and w/b ratio did not have a significant influence on the corrosion rates in submerged conditions.

The range of $TIC_{corr}$ values for specimens in the tidal zone over 160 days varied from 95 to 381 C. This range was substantially lower than the $TIC_{corr}$ range for specimens in the splash and spray zone. $TIC_{corr}$ decreased as the cover depth increased. From Figure 7, a cover of 30 mm effectively converted the tidal zone into the submerged zone, as these specimens had very similar corrosion rates. Specimens with a higher w/b ratio yielded larger $TIC_{corr}$ (given the same cover depth).

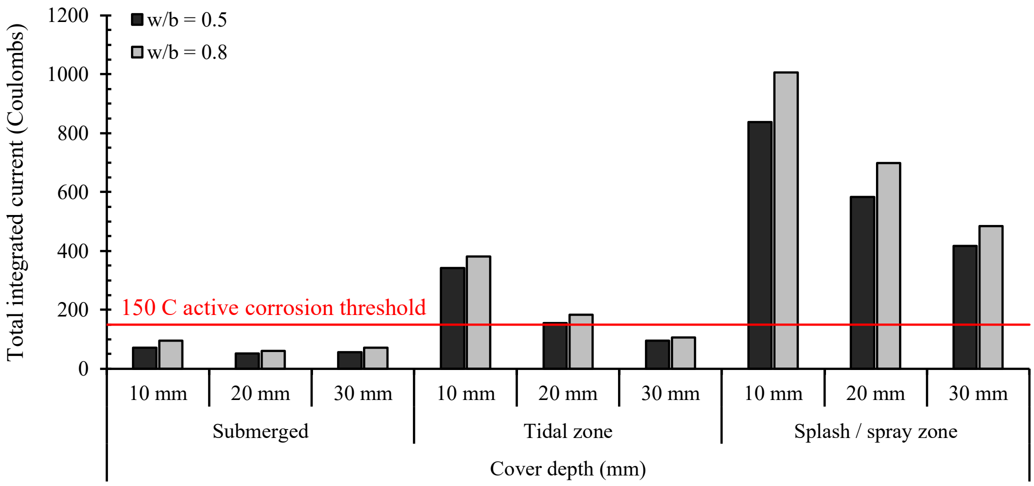


**Figure 7.** Total integrated current in specimens in 3 marine exposure conditions. The red line indicates the value of 150 C, which is the approximate threshold from passive to active corrosion [16].

## 3.2. Influence of Relative Humidity on Average Corrosion Rates

A statistical analysis was carried out to assess the variability in the relative humidity test results across the 5 testing ages (day 60, day 80, day 102, day 120 and day 145) to determine if there was any significant statistical difference. At a 5% level of significance ($\alpha$ = 0.025), the critical t value was determined to be 4.3. From this information, it was determined with 95% confidence that the relative humidity profiles for each exposure condition do not change over time. For this reason, the relative humidity profile was averaged to include only one relative humidity value per set of w/b ratio, cover depth and exposure conditions. Figure 8a,b present the total integrated current and relative humidity measured at various cover depths for the specimens in the simulated exposure zones.

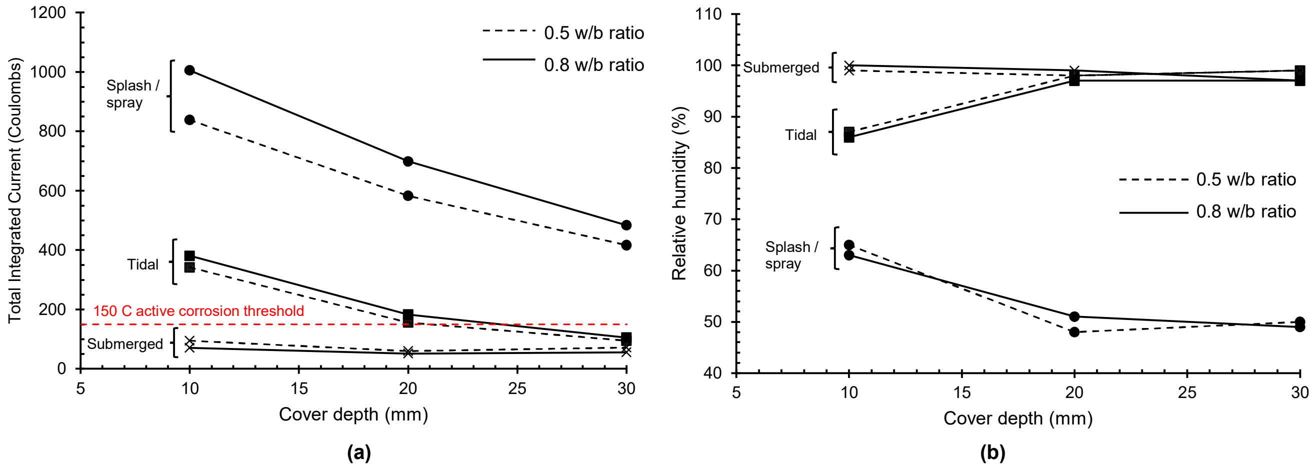


**Figure 8.** Total integrated current (**a**) and relative humidity profiles (**b**) at various cover depths for specimens in the simulated exposure zones.

### 3.2.1. Submerged Zone

Considering the relative humidity profiles for concrete specimens with w/b ratios of 0.5 and 0.8 in the submerged exposure zone shown in Figure 8b, two observations can be made. Firstly, the relative humidity exceeded 97% for all cover depths. The second observation is that at a w/b ratio of 0.5, the relative humidity reduced to 97% at a cover of 30 mm, whereas at 10 and 20 m cover depths, the relative humidity was approximately 100%. The same was not observed for specimens with a w/b ratio of 0.8 that had a relative humidity of approximately 100% at all the cover depths. This can be attributed to the difficulty of water penetrating the deeper parts of the concrete with such a relatively dense pore structure at a w/b ratio of 0.5. A similar phenomenon was found by Ryu, Ko and Noguchi [17] who showed that the moisture content of concrete with a w/b ratio of 0.3 does not reach 100% at any depth that exceeds 10 mm.

The $TIC_{corr}$ values recorded for specimens in the submerged exposure zone for all 3 cover depths and presented in Figure 8a were well below the 150 C threshold for active corrosion for both w/b ratios of 0.5 and 0.8. It is deduced that the high moisture content or relative humidity in the concrete stifled the supply of oxygen to the steel, hence preventing active corrosion.

#### 3.2.2. Tidal Zone

From Figure 8b, the relative humidity for specimens in the tidal zone close to the surface of the concrete (10 mm depth) was lower than the relative humidity deeper in the concrete (30 mm) for all the specimens. Considering that relative humidity readings were taken at the end of the 6 h drying cycle, it is surmised that the surface water had evaporated from the concrete's surface resulting in the lower relative humidity.

The rate and severity of the moisture loss in concrete are dependent on the environmental conditions. Concrete directly exposed to sun and wind will dry faster than concrete sheltered from the elements. Seasonal changes that influence the temperature and climate also heavily influence the rate at which concrete dries. Hunkeler [18] showed that while the moisture content can be influenced by as much as 30% within the first 10 mm of concrete cover, short-term environmental factors do not influence the internal moisture content of concrete beyond a certain depth. This was observed in specimens in the tidal zone, which showed no difference in the relative humidity values for cover depths exceeding 20 mm.

The w/b ratio did not have a significant influence on the relative humidity profiles of the specimens. This was not expected as research has shown that a lower w/b ratio dries out more slowly owing to (i) a lower amount of free evaporable water in the concrete and (ii) a more refined pore structure that inhibits the escape of moisture [19]. This point is not reflected in the results, possibly because in the laboratory environment, the rate of drying is too slow in the relatively short period of drying to have a large influence.

Referring to Figure 8a, for specimens with a cover depth of 10 mm, the $TIC_{corr}$ was substantially higher than that of the specimens with cover depths of 20 mm and 30 mm. This trend was found in specimens with both w/b ratios, although the specimens with the 0.8 w/b ratio and less dense pore structure tended to have a higher $TIC_{corr}$ at 10 mm than the 0.5 w/b ratio. The difference in the $TIC_{corr}$ values for specimens with a w/b ratio of 0.5 and those with a w/b ratio of 0.8 became somewhat less for higher cover depths. This difference in $TIC_{corr}$ values cannot be attributed to a difference in moisture content as the relative humidity profiles were very similar for specimens of both w/b ratios.

For specimens with a high cover depth, 6 h is not sufficient time for the concrete to dry to the level of the steel. Reducing the concrete cover thickness lessens the path that oxygen is required to travel from a structure's surface to the embedded steel [20]. The faster that oxygen can travel to reinforcing steel in concrete, the more oxygen is available for the cathodic reaction to proceed.

In addition, a layer of sessile organisms as found on RC elements in the tidal zone can further slow down the drying of the cover layer and therefore inhibit the movement of oxygen into the concrete as a result of saturated or partially saturated pores. This was not investigated in this study, but this phenomenon could offer a natural buffer for chloride-induced corrosion [21].

#### 3.2.3. Splash and Spray Zone

The relative humidity for specimens in the splash and spray zone presented in Figure 8b at 10 mm was approximately 65%, while at 20 and 30 mm, the relative humidity was closer to 50%. The higher relative humidity at the concrete's surface was the result of the regular splashing, while the concrete beyond a cover depth of 20 mm remained largely at equilibrium. At a relatively low relative humidity, oxygen was able to diffuse through the pore system and facilitate corrosion in the specimen. This was supported by the $TIC_{corr}$ values indicating active corrosion values that are shown in Figure 8a.

In the splash and spray zone, the cover depth had a strong influence on the $TIC_{corr}$. As the cover depth increased, the $TIC_{corr}$ decreased. This was attributed to the longer distance that deleterious substances (such as oxygen) had to travel in order to reach the surface of the steel. For these specimens, it is possible that the electrical resistivity of the concrete was the main limiting factor in controlling the corrosion rate [11].

The laboratory simulation used lower concrete quality and lower cover depths than current recommended practice for concrete elements in the marine environment. This may have led to an artificially large degree of moisture variations at the depth of the reinforcing. The actual degree of moisture variation on newer structures constructed according to modern standards may be significantly lower.

## 4. Factors Influencing Corrosion in the Marine Exposure Zones

### *4.1. The Influence of Cover Depth on Reinforcement Corrosion*

In general, as is already well understood, a higher cover depth inhibits the movement of corrosion agents through the concrete cover and slows the process of reinforcement corrosion. However, the influence that a larger cover depth had on reducing the corrosion rate was found to be dependent on the environmental exposure conditions. Reinforcement corrosion in concrete in the splash and spray zone was highly dependent on the cover depth, while in contrast, changing the cover depth had virtually no effect on specimens in the submerged condition, as the fully saturated pores limited the amount of oxygen available at the steel. The corrosion rate decreased with an increase in cover depth in the tidal zone, and it was found that a cover of 30 mm or more effectively changed the tidal zone exposure into a submerged zone exposure.

At lower cover depths, oxygen was able to reach the rebar in the splash and spray zone faster by diffusing through the air-filled pores. Conversely, pores in concrete in the tidal zone were partially or fully saturated with sea water, and therefore the diffusion of oxygen was hindered. Only at higher cover depths did the tidal and splash and spray zones experience similar levels of deterioration. The low levels of deterioration at high cover depths in both exposure zones was due to oxygen having a longer path to travel before reaching the rebar and due to the reduced influence of the exposure conditions on the internal relative humidity deeper in the concrete.

### *4.2. The Influence of w/b Ratio on Reinforcement Corrosion*

The experimental results show that a lower w/b ratio led to a reduction in the corrosion rate. As with the cover depth, the impact of changing w/b ratio on $TIC_{corr}$ had different results on the specimens depending on the environmental conditions. For concrete in the splash and spray zone, the increase in the w/b ratio led to higher relative humidity, which yielded a reduction in the diffusion of oxygen and hence a decrease in corrosion rates. In contrast, a change in the w/b ratio of concrete had no significant effect on the relative humidity and subsequently the reinforcement corrosion in concrete in the submerged zone. Increasing the w/b ratio of the concrete in the tidal zone had only a minor effect on reinforcement corrosion rates. This small change was due to a denser pore structure taking longer to dry, resulting in suppression of the cathodic reaction through oxygen deprivation. However, this effect was so small for concrete in the tidal zone that it may be considered negligible. The results show that for ordinary Portland cement (OPC), the cover depth is more effective at reducing the corrosion rate via cathodic control than the "quality" of the cover (in this case inferred from the w/b ratio).

### *4.3. The Influence of Exposure Environment on Rebar Corrosion*

The exposure environment strongly influenced the rate of rebar corrosion. This was linked to the moisture distributions of the concretes under different environmental conditions. The main finding from the research presented in this paper is that concrete exposed to the splash and spray and tidal zones may be expected to deteriorate at significantly different rates. For concrete submerged and partially or completely saturated with water, oxygen availability at the steel surface was limited. High relative humidity limited the supply of oxygen to the steel and hence prevented active corrosion. The experimental results confirm the widely accepted principle that submerged concrete is less vulnerable to corrosion as a result of insufficient oxygen.

Specimens exposed to a splash and spray environment performed as expected. Relatively lower moisture contents allowed oxygen to diffuse through the pore system and facilitate corrosion in the specimens in this exposure zone. In the case of these specimens, it was deduced that the electrical resistivity of the specimen was the main limiting factor in controlling the corrosion rate (and not cathodic control as with tidal and submerged specimens).

For concrete exposed to 6 h cycles of wetting and drying, the corrosion rate was significantly lower when the cover depth was high. This was because the pores surrounding the steel were still partially or fully saturated with water and had not had sufficient time to dry out. As a result, oxygen diffused more slowly through the cover layer. Consequently, where the concrete in the tidal zone has a drying time of 6 h and cover depths that are sufficiently high (in this case 30 mm), the steel is oxygen-deprived, and corrosion is suppressed. In the tidal zone at 10 mm cover, lower moisture contents and higher corrosion rates were recorded. This was attributed to water in the pores being able to dry from the surface 10 mm of concrete in the 6 h drying time. The pores were therefore partially saturated and allowed the rapid ingress of oxygen to the rebar, resulting in higher corrosion rates.

### *4.4. Controlling the Corrosion Rate by Limiting Drying Time*

Research by Hong and Hooton [9] and Otieno et al. [22] showed that the duration of wetting and more importantly the drying of concrete had a significant effect on the corrosion rate of steel within the concrete. These studies found that for shorter drying times, the rate of corrosion was significantly reduced, especially for concretes with low w/b ratios and high cover depths.

If one considers that in addition to chloride ions, oxygen is required to sustain corrosion propagation, limiting the oxygen available at the steel surface effectively suppresses corrosion. Limiting the quantity of oxygen available can be achieved by preventing drying to the level of the reinforcement, which inhibits the reduction of oxygen at the cathode and results in cathodic control of the corrosion rate [4]. For concrete members experiencing short drying times or members with high cover depth and/or concrete of low penetrability, drying to the level of steel is decreased, and the effects of cyclic wetting and drying will not impact the steel, so that the steel may be considered to be in a member that behaves as if it is permanently submerged.

## 5. Conclusions

The experimental work using simulated marine environments presented in this paper confirmed the expectation that the corrosion of the embedded steel in concrete in marine exposure zones is closely linked to the availability of oxygen. Oxygen is required for the cathodic reaction in the corrosion cell, and without it, the corrosion rate becomes cathodically controlled. The concrete cover thickness was found to be more effective at cathodic control of the corrosion rate than the concrete quality (inferred from the w/b ratio) for both the splash and spray as well as the tidal zones for OPC concrete. However, if these parameters are appropriately optimized, the effects of the expected harsh conditions in the marine tidal zone can be minimized.

The main conclusion from the laboratory and field studies presented in this paper is that it is imperative to take a holistic approach in order to adequately assess the potential risk of corrosion in steel-reinforced concrete structures. Such an approach should take into consideration all the relevant factors that can affect corrosion in a given marine exposure environment, including cover depth, concrete quality, chloride content, ambient temperature and the related indirect factors, such as oxygen availability.

The corrosion of embedded reinforcing steel can be controlled in design and construction through two primary parameters—the concrete w/b ratio and the cover thickness. If sufficient concrete quality (low w/b ratio) and cover thickness are provided, the concrete may not dry to the level of steel to an extent where reinforcement corrosion is facilitated. As a result, reinforced concrete in the marine tidal zone can perform as if it were permanently submerged, which results in the corrosion rate being reduced to a level where significant damage does not occur.

The application of these research findings would be to infrastructure that is primarily exposed to tidal and submerged marine conditions. Common examples include concrete pipes where many pipelines have been in service for more than 50 years despite sometimes having a cover to reinforcement of as little as 20 mm, as well as parts of marine structures exposed to the tidal zone, such as piles, coping units and quay walls.

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## References

1. *BS EN 206:2013*; Concrete—Specification, Performance, Production and Conformity. British Standards Institution: London, UK, 2013.
2. Otieno, M.; Thomas, M. Chapter 7: Marine Exposure Environments and Exposure Sites. In *Marine Concrete Structures: Design, Durability and Performance*; Alexander, M.G., Ed.; Woodhead Publishing: Sawston, UK, 2016; pp. 171–196.
3. Alexander, M.; Beushausen, H.; Otieno, M. Service life and durability design of RC structures: General considerations and selected Southern African perspectives and experiences. *Sustain. Resilient Infrastruct.* **2021**, 1–13. [CrossRef]
4. Bertolini, L.; Elsener, B.; Pedeferri, P.; Redaelli, E.; Polder, R.B. *Corrosion of Steel in Concrete: Prevention, Diagnosis, Repair*, 2nd ed.; Wiley-VCH: Weinham, Germany, 2013.
5. Ahmad, S. Reinforcement corrosion in concrete structures, its monitoring and service life prediction—-A review. *Cem. Concr. Compos.* **2003**, *25*, 459–471. [CrossRef]
6. Andrade, C.; Alonso, C.; Sarría, J. Corrosion rate evolution in concrete structures exposed to the atmosphere. *Cem. Concr. Compos.* **2003**, *24*, 54–64. [CrossRef]
7. Beushausen, H.; Ndawula, J.; Helland, S.; Papworth, F.; Linger, L. Developments in defining exposure classes for durability design and specification. *Struct. Concr.* **2021**, *22*, 2539–2555. [CrossRef]
8. Polder, R.B. Durability of marine concrete structures field investigations and modelling. *Heron* **2005**, *50*, 133–153.
9. Hong, K.; Hooton, R.D. Effects of cyclic chloride exposure on the penetration of concrete cover. *Cem. Concr. Res.* **1999**, *29*, 1379–1386. [CrossRef]
10. Gjorv, O.E.; Vennesland, O.; El-Busaidy, A.H.S. Diffusion of dissolved oxygen through concrete. *Mater. Perform.* **1987**, *25*, 12.
11. Raupach, M. Investigations on the influence of oxygen on corrosion of steel in concrete-Part 2. *Mater. Struct.* **1996**, *29*, 226–232. [CrossRef]
12. Walsh, M.T.; Sagüés, A.A. Steel corrosion in submerged concrete structures—Part 1: Field observations and corrosion distribution modeling. *Corrosion* **2016**, *72*, 518–533. [CrossRef]
13. Mehta, P.K. *Concrete in the Marine Environment*; Elsevier Applied Science: London, UK, 1991.
14. *ASTM G109-07*; Standard Test Method for Determining Effects of Chemical Admixtures on Corrosion of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments. ASTM International: West Conshohocken, PA, USA, 2013.
15. Rauf, S.B. Chapter 2: DC Circuit Analysis and Basic Electronic Devices. In *Electrical Engineering for Non-Electrical Engineers*, 2nd ed.; Fairmont Press: Atlanta, GA, USA, 2017.
16. Trejo, D.; Halmen, C.; Reinschidt, K. *Corrosion Performance Tests for Reinforcing Steel in Concrete: Technical Report*; Texas Transportation Institute: Austin, TX, USA, 2009.

17. Ryu, D.W.; Ko, J.; Noguchi, T. Effects of simulated environmental conditions on the internal relative humidity and relative moisture content distribution of exposed concrete. *Cem. Concr. Compos.* **2011**, *33*, 142–153. [CrossRef]
18. Hunkeler, F. Corrosion in Reinforced Concrete: Processes and Mechanisms. In *Corrosion in Reinforced Concrete Structures*; Bohni, H., Ed.; Woodhead Publishing Limited: Abington, UK, 2005; pp. 1–45.
19. Nilsson, L.O. Long-term moisture transport in high performance concrete. *Mater. Struct.* **2002**, *35*, 641–649. [CrossRef]
20. Hawkins, C.; McKenzie, M. Environmental Effects on Reinforcement Corrosion Rates. In Proceedings of the Fourth International Symposium on Corrosion of Reinforcement in Concrete Construction, Cambridge, UK, 1–4 July 1996.
21. Coombes, M.A.; Viles, H.A.; Naylor, L.A.; La Marca, E.C. Cool barnacles: Do common biogenic structures enhance or retard rates of deterioration of intertidal rocks and concrete? *Sci. Total Environ.* **2017**, *580*, 1034–1045. [CrossRef] [PubMed]
22. Otieno, M.; Golden, G.; Alexander, M.; Beushausen, H. Acceleration of steel corrosion in concrete by cyclic wetting and drying: Effect of drying duration and concrete quality. *Mater. Struct.* **2019**, *52*, 1–14. [CrossRef]