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Reinforced Concrete Durability in Response to Aggregate Proportioning

A. López-González, M. Balancán-Zapata, L. Diaz-Ballote, P. Castro-Borges[*]

Centro de Investigación y de Estudios Avanzados del IPN Unidad Mérida, Antigua Carretera a Progreso Km. 6, 97310 Mérida, Yucatán, México;
[*]E-mail: pcastro@mda.cinvestav.mx

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In tropical marine environments, concrete structure durability is affected by atmospheric chlorides, and changes in temperature and relative humidity. These factors lead to corrosion of steel reinforcement and diminished structure use life. Refining aggregate proportioning is a viable alternative for controlling corrosion and improving structure performance in aggressive environments. A comparison in terms of durability was made between aggregate proportioning in the American Concrete Institute (ACI) and O'Reilly concrete design systems. Prismatic concrete test specimens were made using one of the systems and either a 0.45 or 0.65 water to cement (w/c) ratio. All specimens contained six carbon steel reinforcement bars at three different depths (1.5, 2 and 3 cm). They were exposed to a tropical marine environment for 24 months. Electrochemical behavior of the reinforcement was evaluated using the linear polarization resistance technique, corrosion potential and electrical resistance. Specimens made with the O'Reilly method and a w/c = 0.65 had higher electrochemical activity values than those made with the ACI method and the same w/c. However, both were still in the passivation stage. Specimens made with a w/c = 0.45, for either method, did not differ in their behavior. Use of a cumulative data analysis allowed identification of small and incipient differences that revealed the influence of concrete cover, surface orientation and aggregate proportioning method on the durability of reinforced concrete in this climate.

Keywords: reinforced concrete, marine environment, durability, electrochemical behavior.

1. INTRODUCTION

Corrosion of steel reinforcement in structures in tropical marine environments is of worldwide concern because it directly affects infrastructure durability and results in costly repairs [1, 2]. The tropical marine environment is one of the most atmospherically aggressive [3]. Its combination of rainfall, winter storms, drought, etc. affects the electrochemical behavior of reinforcing steel, causing it to corrode and consequently diminishing structure use life [4]. Penetration of aggressive agents from the environment into the concrete matrix occurs through a pore network via diffusion [5], absorption, or a combination thereof. In conjunction with changes in concrete internal relative humidity (RH) and temperature (T), these factors increase penetration rate and electrochemical reaction, leading to corrosion of steel reinforcement [6]. The pore network can be controlled with an adequate aggregate ratio, which can produce a more compact mixture with a minimum of voids and a consequent reduction in the diffusion process.

The present study objective was to compare two aggregate proportioning calculation methods (American Concrete Institute (ACI) [7, 8] and the Cuban O'Reilly system [9]) in terms of durability after twenty-four months exposure to a tropical marine environment.

2. TESTING METHODOLOGY

Twelve prismatic test specimens were designed, six using the ACI method and six with the O'Reilly method (OM). All specimens were reinforced with six 3/8" diameter steel bars placed at 1.5, 2 and 3 cm depth inside the concrete cover. Water/cement (w/c) ratios of 0.45 and 0.65 were used. Specimens were exposed in a tropical marine environment at the Centre for Research and Advanced Studies (Centro de Investigación y de Estudios Avanzados – CINVESTAV) Telchac Marine Station in Yucatan, Mexico. They were placed 50 m from shoreline with the main surface facing northeast, the direction of the prevailing winds at this location (Figures 1 and 2).

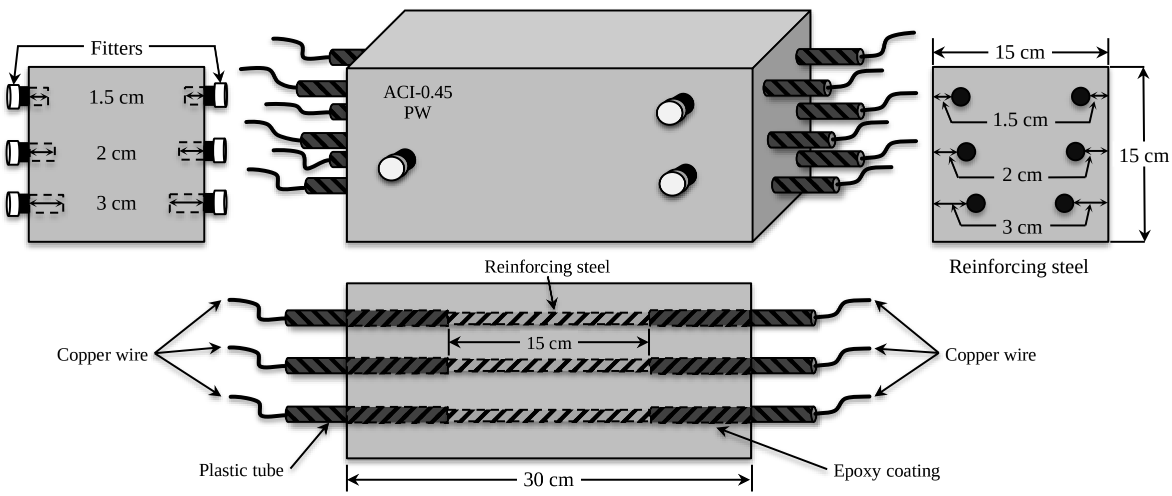


Figure 1. Schematic illustration of a concrete specimen.

Small internal devices (fitters) were inserted into the front and rear surfaces of the specimens to monitor internal concrete T and HR using a portable measurer (Figure 3). Electrochemical behavior was monitored and interpreted using linear polarization resistance (Rp), corrosion potential (E_{corr}) and concrete resistivity (ρ) measured with a commercial corrosimeter [10]. Concrete ingredients included Portland cement and crushed aggregates from local sources.

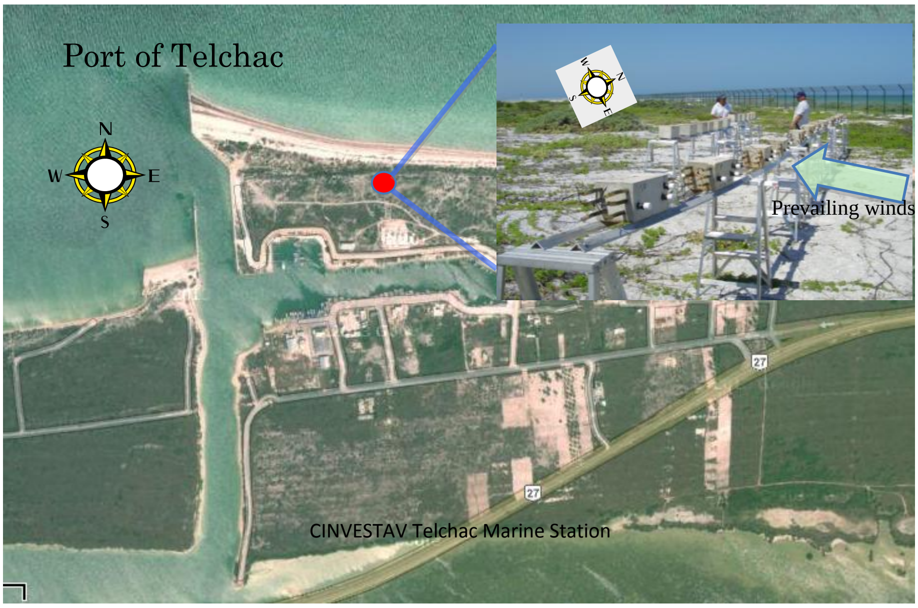


Figure 2. CINVESTAV Telchac Marine Station (red dot) and exposure site, Yucatan, Mexico.

Figure 3. Measuring concrete internal RH and T.

2.1 ACI mixture design method

The American Concrete Institute [7, 8] system is probably the most widely used calculation method in concrete structure design. It proposes that aggregate size should be as large as possible, surpassing neither one fifth of the smallest dimension of the element to be formed nor three quarters of the minimum separation between reinforcements. In the case of floors or slabs, aggregate size must not be greater than one third the thickness of the floor. To choose the most adequate consistency, the lowest possible settling is used that is compatible with correct concrete placement in the structure. The settling values recommended in the Abrams cone as a function of different structure types can be checked in a table. Maximum aggregate size is chosen based on identified consistency, the chosen maximum aggregate size, its shape, granulometry and the amount of incorporated air. A table can be used to determine the amount of water needed per cubic meter of concrete, which is independent of the amount of cement used.

The ACI method fixes the w/c ratio as a function of durability or compression resistance. If durability is used, the maximum w/c ratio is found in a table based on structure type and service conditions. If design is focused on compressive resistance, the ratio is found in tables based on whether or not air is incorporated into the concrete. Once the w/c ratio and amount of water are known, the amount of cement per cubic meter of concrete can be calculated.

The amounts of coarse and fine aggregates are then calculated. Considering docility, the highest possible amount of coarse aggregate is used to attain maximum resistance, the minimum amount of mix water and the least retraction. This is calculated using laboratory evaluations. However, if these data are not available, tables can be used to find an acceptable figure. These tables provide an amount of coarse aggregate per concrete unit volume as a function of maximum aggregate diameter, docility and the fine aggregate fineness module. The amount of fine aggregate can be calculated by the absolute volumes or weights methods [7, 8].

2.2 O'Reilly mixture design method

Proposed by Vitervo O'Reilly (1993), this method is used in Cuba and other countries in the Americas and Africa [9]. Among its principal advantages is the savings in the amount of cement required compared to other methods. Indeed, it can result in a 15% or greater reduction in cement use per cubic meter of concrete, with consequently substantial financial savings in the construction industry. The overall goal is to save as much cement as possible under existing technological conditions without requiring additional investments or the importation of chemical additives for concrete mixtures. O'Reilly proposes a method based on calculation of the dry characteristics to be used and mixture design as a function of these characteristics. This arises from the existence of a quantitative influence of aggregate shape on cement use.

Briefly, the percentage combination of coarse aggregates and sand that produces maximum volumetric weight (i.e. minimum void content) is determined experimentally, and void content calculated to determine paste volume. Cement and water contents are then calculated based on factors depending on the w/c ratio and desired mixture consistency.

2.3 Evaluation criteria

Active corrosion (depassivation) was identified using an $i_{corr} > 0.2\ \mu A/cm^2$, which is accepted as the threshold for steel corrosion in concrete [11, 12]. For E_{corr}, the criterion was ASTM C876 [13], and for ρ it was the criterion ASTM G57 [14].

3. RESULTS

3.1 Concrete Internal Temperature (T)

Internal temperature during the two-year study period did not differ between the specimens prepared using the ACI or OM methods (Figures 4 and 5). In the ACI specimens, mean temperature ranged from 24 to 35 °C in specimens prepared with a w/c = 0.45 (Figure 4a), and from 24 to 38 ºC in those prepared with a w/c = 0.65 (Figure 4b). Variation in response to cover thickness (1.5, 2 and 3 cm) was ±0.6 ºC, indicating minimal influence. Temperature ranges for the OM specimens were very near those for the ACI specimens and remained within the same ranges (Figures 5a and 5b).

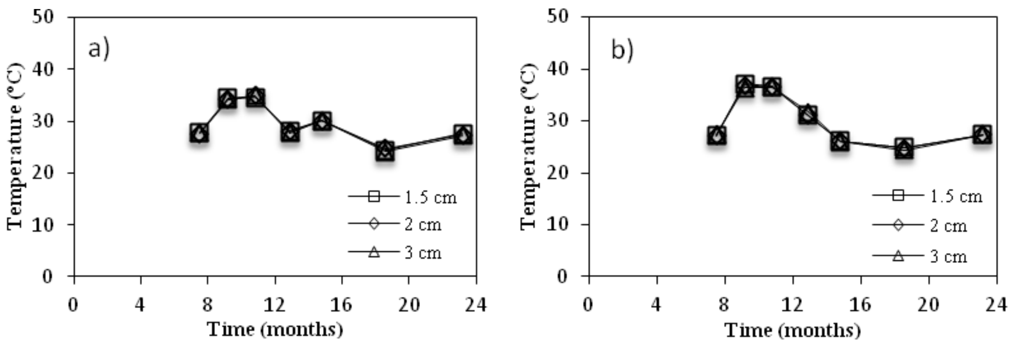


Figure 4. Average temperature of ACI specimens exposed in a tropical marine environment for 24 months: a) w/c = 0.45; b) w/c = 0.65.

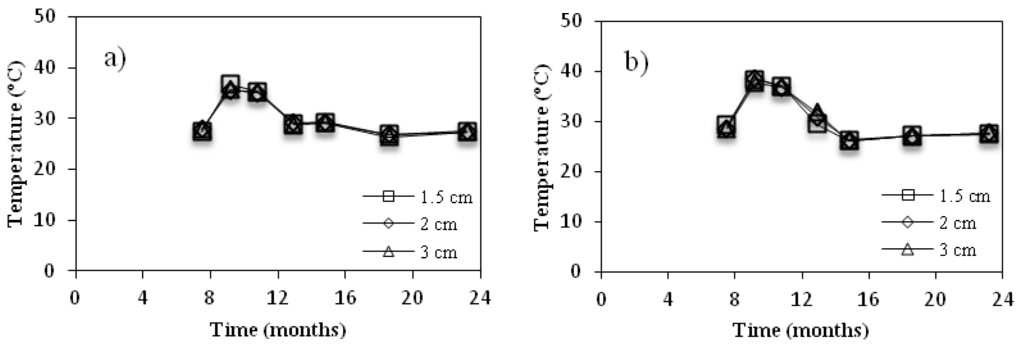


Figure 5. Average temperature of OM specimens exposed in a tropical marine environment for 24 months: a) w/c = 0.45; b) w/c = 0.65.

Aggregate proportion had no appreciable effect on concrete internal matrix T. However, higher T values were observed in the w/c = 0.65 treatments, suggesting that matrix density affected T behavior.

3.2 Concrete Internal Relative Humidity (RH)

Both the ACI and O'Reilly methods resulted in similar internal RH behavior, with the same peaks at the same times, although of different intensities (Figures 6 and 7). Values oscillated between 65 and 95%, with no observed effect from changes in w/c or cover thickness. However, both the ACI and OM specimens with w/c = 0.45 exhibited greater variation in RH values during the earliest months. This difference could be attributed to the amount of stone aggregate in the concrete since the type of rock used to make the aggregate tends to retain water [15]. This could result in lower permeability in the ACI specimens because their stone aggregate content was lower than in the OM specimens.

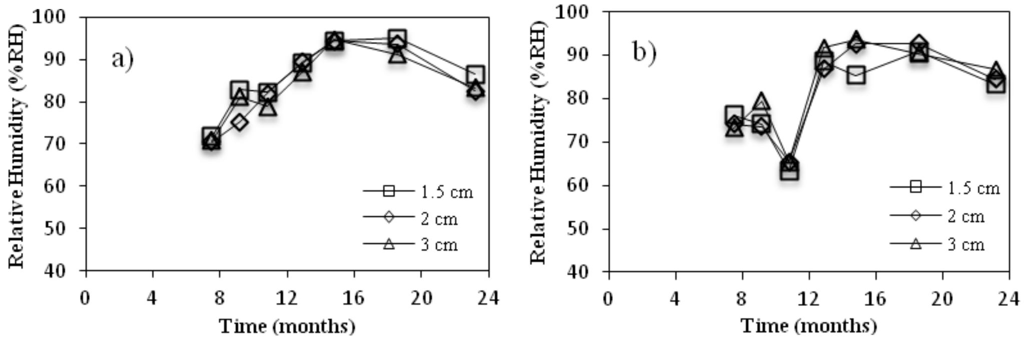


Figure 6. Average internal RH of ACI specimens exposed in a tropical marine environment for 24 months: a) w/c = 0.45; b) w/c = 0.65.

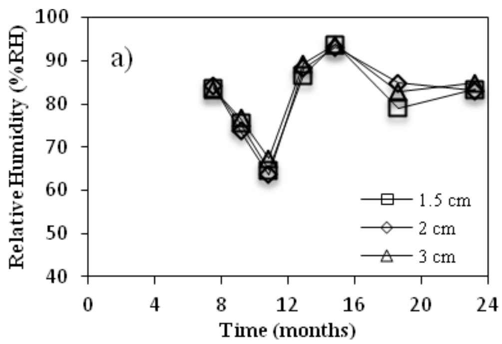


Figure 7. Average internal RH of OM specimens exposed in a tropical marine environment for 24 months: a) w/c = 0.45; b) w/c = 0.65.

3.3 Electrochemical behavior

Corrosion potential and rate, and concrete resistivity for both aggregate proportion calculation methods and both w/c ratios were analyzed in terms of specimen surface orientation: prevailing winds (PW) and non-prevailing winds (NPW). In all cases, PW surfaces had slightly higher electrochemical values than NPW surfaces (Figures 8 - 15).

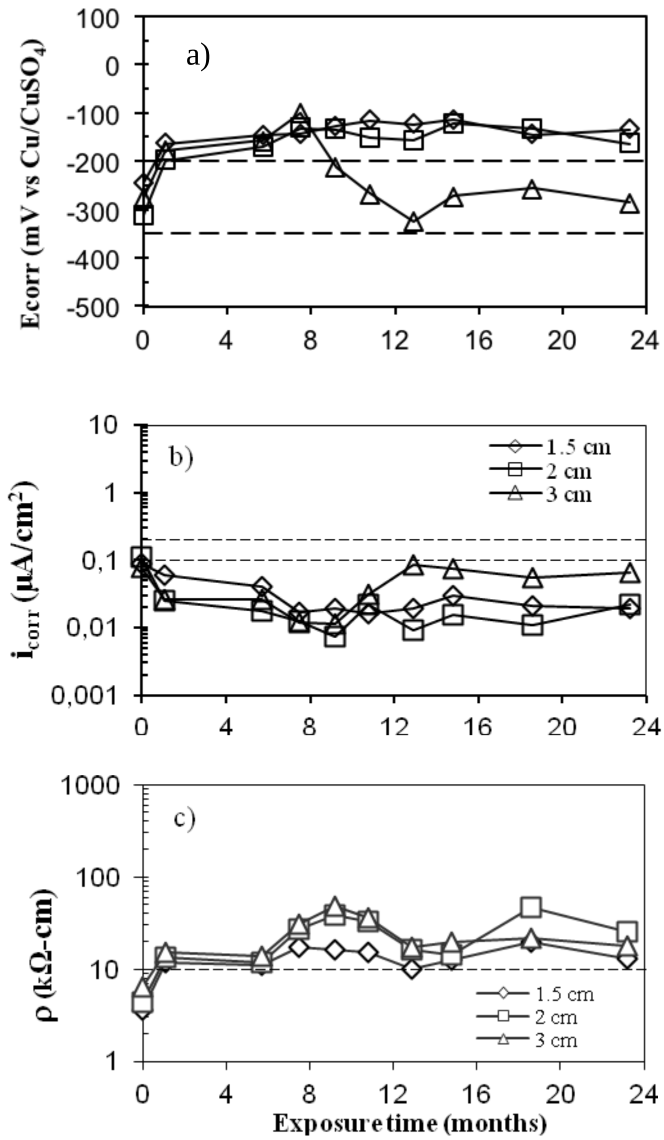


Figure 8. Electrochemical measurements of ACI specimens with a w/c = 0.45, prevailing winds surface (PW): (a) Corrosion potential; (b) Corrosion rate; (c) Resistivity (ρ).

Initial i_{corr} and E_{corr} values indicated risk although this behavior can be attributed to formation of the passive layer on the steel. In the following months, both the ACI and OM w/c = 0.45 treatments had i_{corr} values below 0.1 µA/cm^2 and E_{corr} values above -250 mV. In the OM specimens with w/c = 0.65, i_{corr} values exhibited uncertain behavior after twelve months exposure. Nonetheless, the overall behavior for both methods at both concrete qualities was conservative during the first 24 months of exposure. Resistivity (ρ) also had initial values indicating risk (<10 kΩ-cm), although they remained above this level during the remaining time, indicating a low corrosion risk. Concrete cover thickness had no observable effect on electrochemical behavior in any of the treatments.

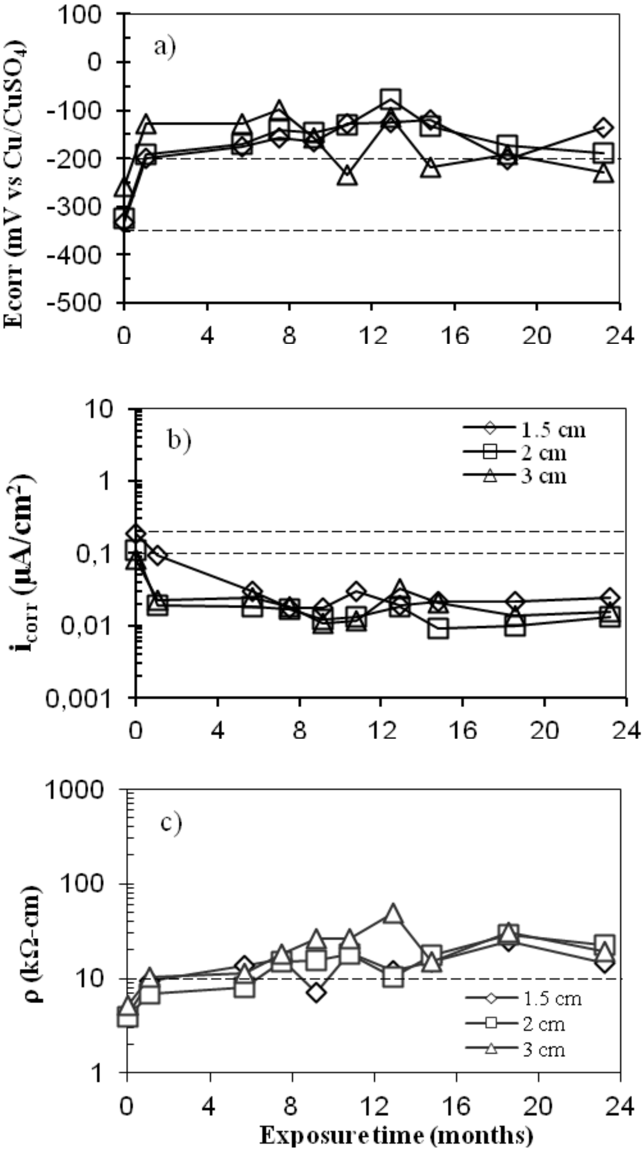
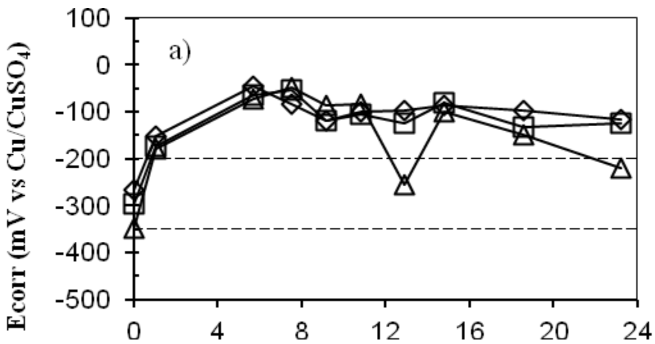


Figure 9. Electrochemical measurements of ACI specimens with a w/c = 0.45, non-prevailing winds surface (NPW): (a) Corrosion potential; (b) Corrosion rate; (c) Resistivity (ρ).



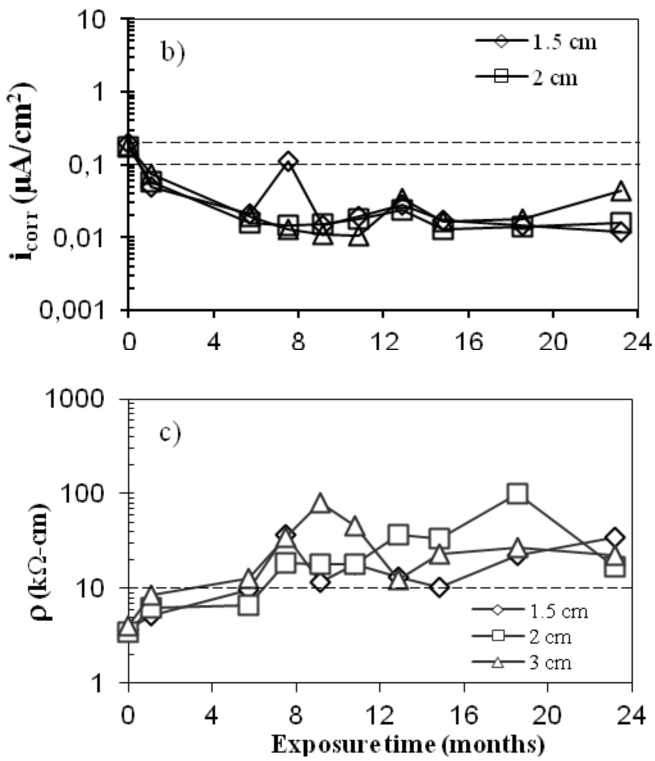
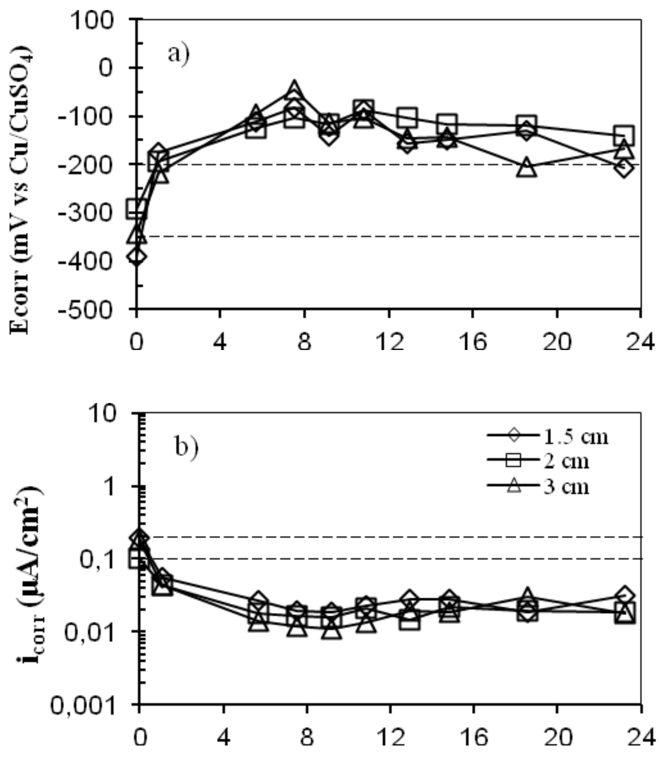


Figure 10. Electrochemical measurements of OM specimens with a w/c = 0.45, prevailing winds surface (PW): (a) Corrosion potential; (b) Corrosion rate; (c) Resistivity (ρ).



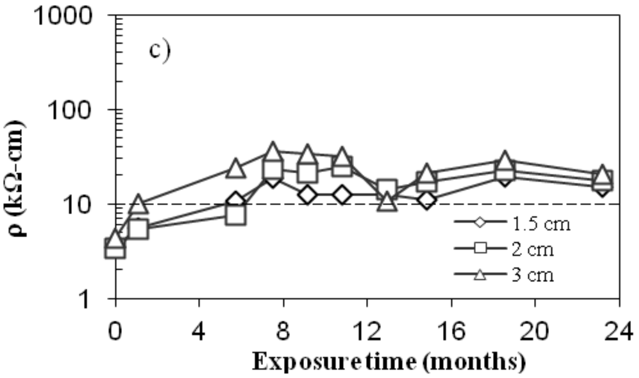


Figure 11. Electrochemical measurements of OM specimens with a w/c = 0.45, non-prevailing winds surface (NPW): (a) Corrosion potential; (b) Corrosion rate; (c) Resistivity (ρ).

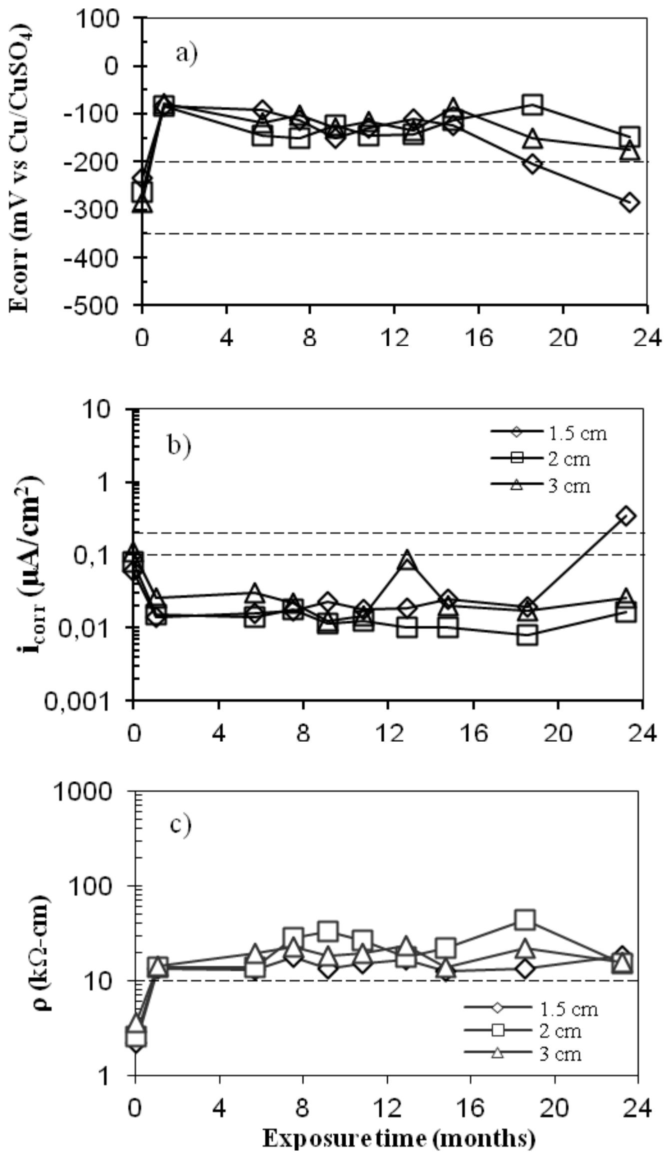


Figure 12. Electrochemical measurements of ACI specimens with a w/c = 0.65, prevailing winds surface (PW): (a) Corrosion potential; (b) Corrosion rate; (c) Resistivity (ρ).

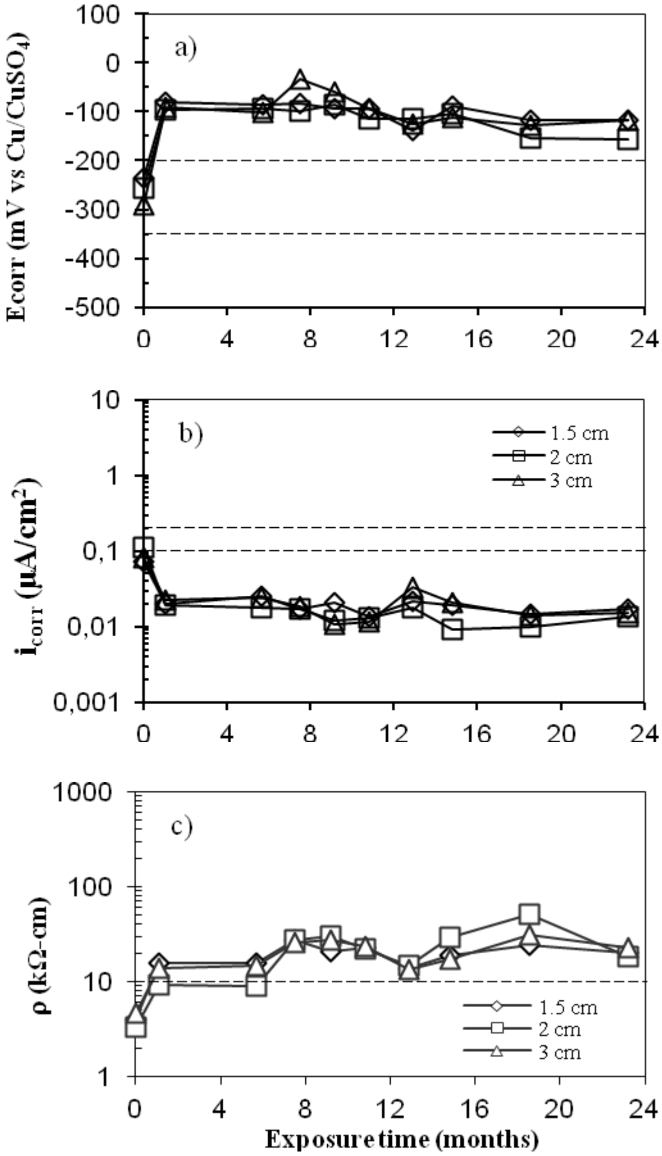
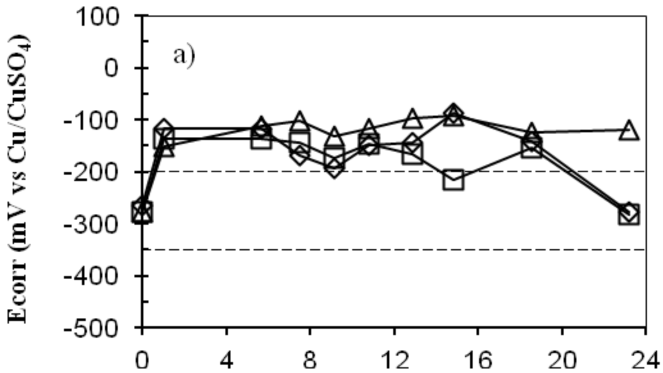


Figure 13. Electrochemical measurements of ACI specimens with a w/c = 0.65, non-prevailing winds surface (NPW): (a) Corrosion potential; (b) Corrosion rate; (c) Resistivity (ρ).



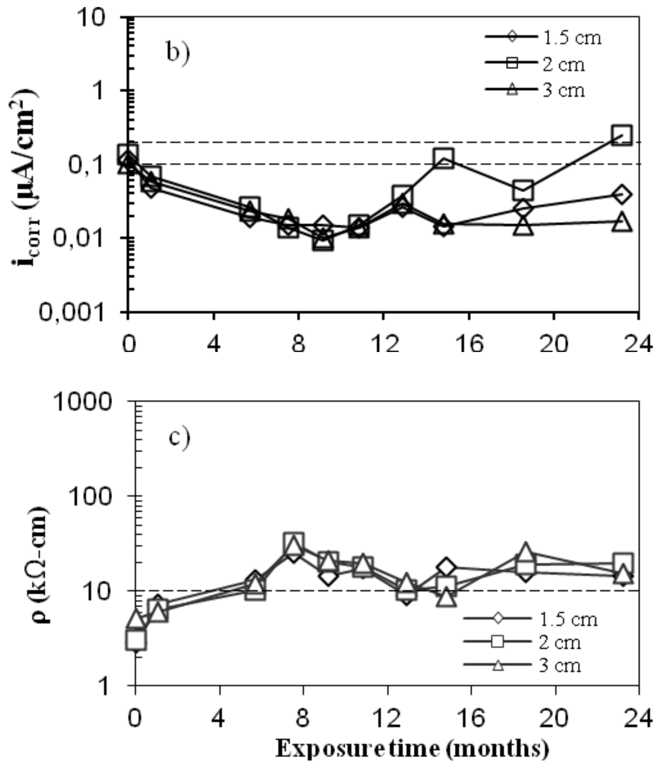
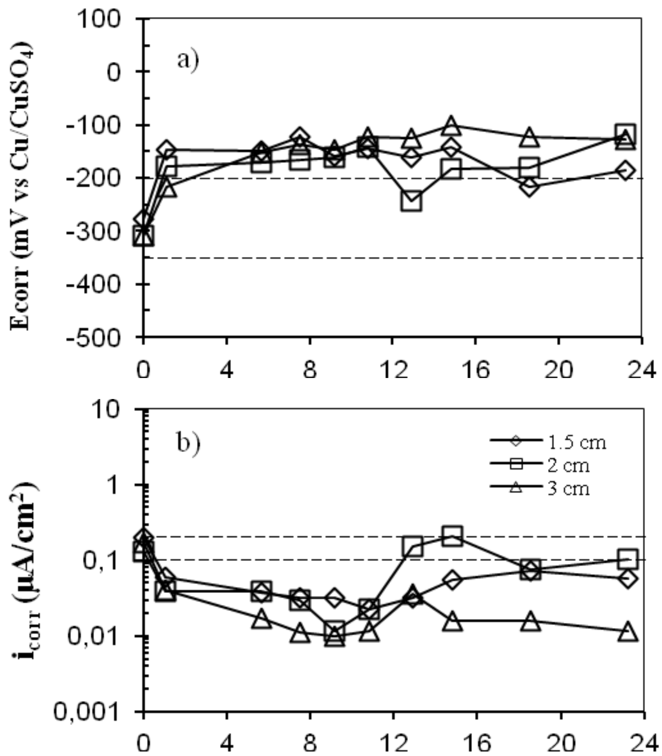


Figure 14. Electrochemical measurements of OM specimens with a w/c = 0.65, prevailing winds surface (PW): (a) Corrosion potential; (b) Corrosion rate; (c) Resistivity (ρ).



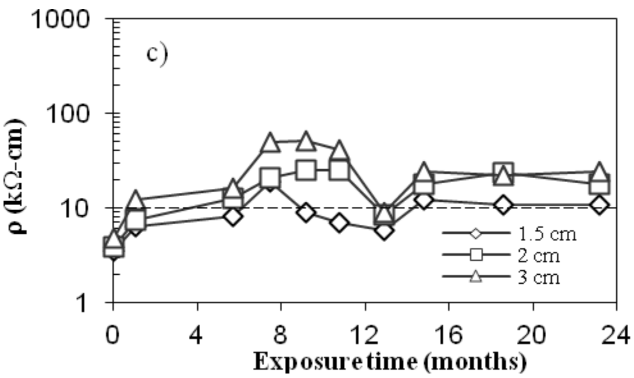


Figure 15. Electrochemical measurements of OM specimens with a w/c = 0.65, non-prevailing winds surface (PW): (a) Corrosion potential; (b) Corrosion rate; (c) Resistivity (ρ).

Predicting future electrochemical behavior in the tested specimens based on the present results (Figures 8 -15) is challenging because the measured changes were still quite minor and disperse. However, the data were analyzed cumulatively to identify any possible effects of surface orientation, internal T and HR, aggregate proportion calculation method and cover thickness over a short time period.

4. DISCUSSION

The influence of orientation, internal T and HR, dossification method and cover thickness can be seen more clearly in graphs of accumulated corrosion rates, i_{accum} (Figures 16 - 19). These also more precisely indicate the moment of greatest corrosion risk [16].

4.1 Surface Orientation

Surfaces facing the PW clearly had i_{accum} values higher than those facing the NPW. The only exception was the NPW surface of the OM w/c = 0.65 treatment, which had higher values (Figure 19b). This one difference can be attributed to the aggregate, which tends to retain water and therefore leads to a more rapid corrosion process. This was uncharacteristic in most of the treatments, highlighting the need to closely monitor future electrochemical behavior in the OM w/c = 0.65 treatment.

Accumulated i_{corr} has been shown to reveal steel depassivation [16], allowing implementation of protective measures in the structure or structural element at risk of corrosion. In contrast, it is much more difficult to identify the proper moment for intervention when evaluating corrosion using point i_{corr} values because real depassivation occurs when the data do not return to the transition zone. For example, in a standard i_{corr} graph the data fluctuate within the transition zone, activating and passivating in response to the generated corrosion products. At the point when only activation data are present the structural element has already experienced physical damage.

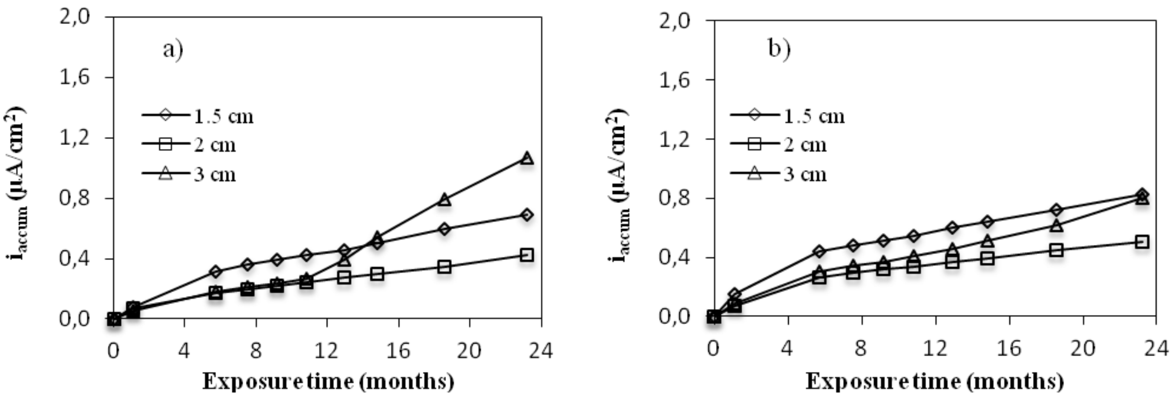


Figure 16. Accumulated corrosion rate (i_{accum}) graphs for ACI specimens with a w/c = 0.45: a) prevailing winds; b) non-prevailing winds.

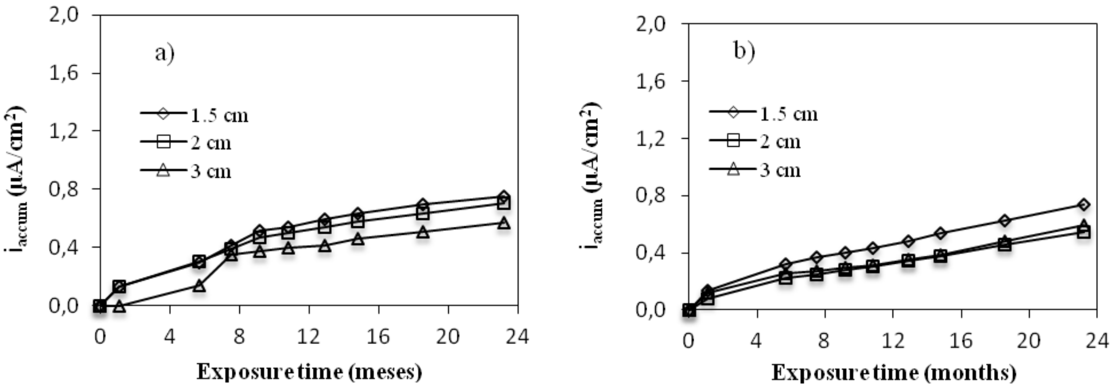


Figure 17. Accumulated corrosion rate (i_{accum}) graphs for OM specimens with a w/c = 0.45: a) prevailing winds; b) non-prevailing winds.

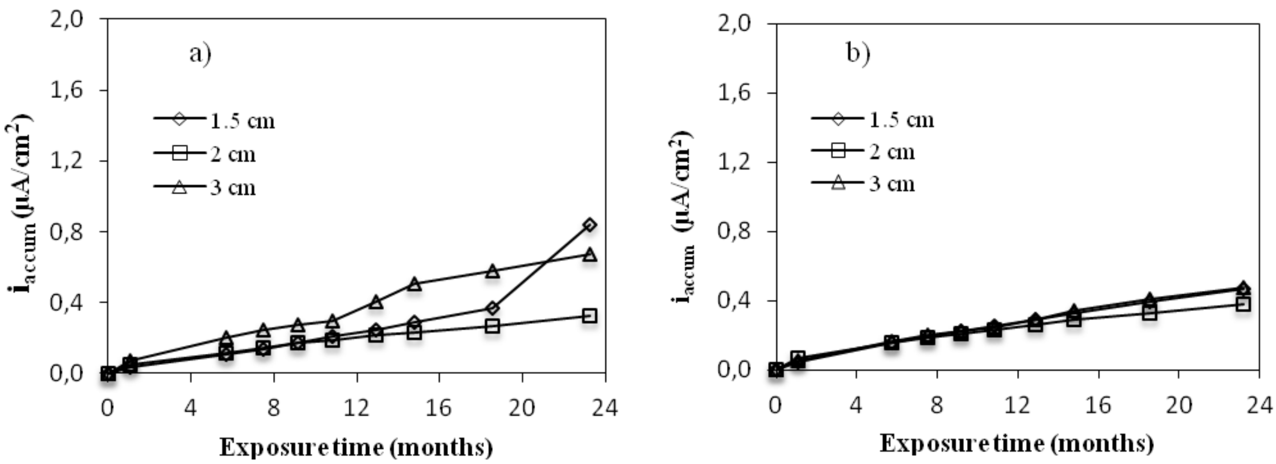


Figure 18. Accumulated corrosion rate (i_{accum}) graphs for ACI specimens with a w/c = 0.65: a) prevailing winds; b) non-prevailing winds.

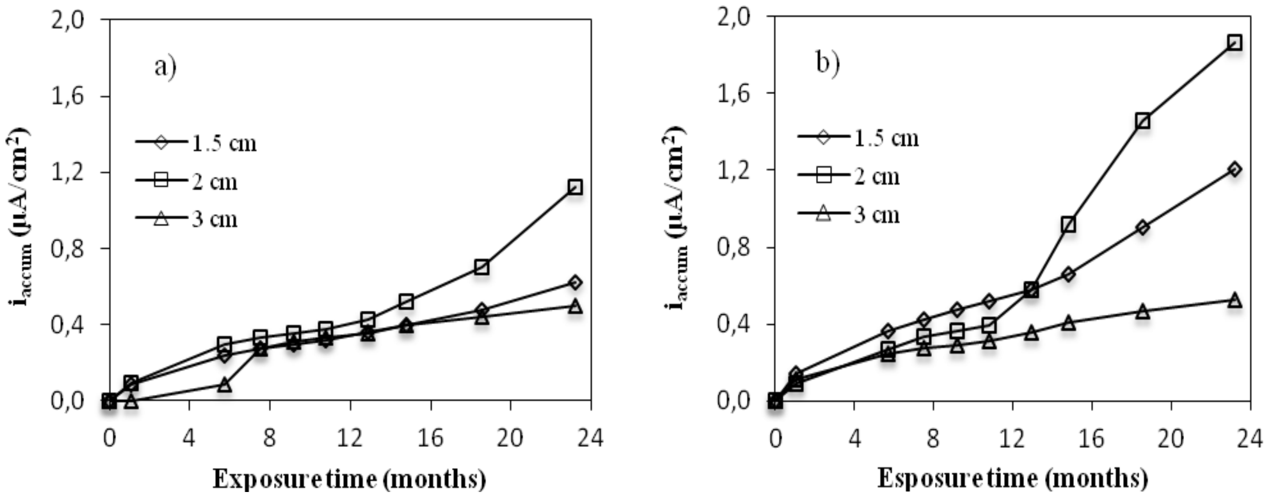


Figure 19. Accumulated corrosion rate (i_{accum}) graphs for OM specimens with a w/c = 0.65: a) prevailing winds; b) non-prevailing winds.

The present results cover a relatively short time period (24 months), meaning the slope changes observed in Figures 16 to 19 are not related to electrochemical activation; indeed, passive i_{corr} values were apparent in Figures 8 to 15. Continued periodic evaluation and cumulative analyses would produce data more representative of environmental influence on steel reinforcement in concrete and help to more exactly identify the correct moment at which to rehabilitate or intervene in the specimens to ensure reinforcement protection. The present data will help in determining when depassivation, and therefore corrosion, has begun. These can then be extrapolated to real structures to identify a structure's electrochemical moment, be it initiation or propagation, and then take measures to ensure structure durability. Accumulated corrosion rate graphs are highly useful in that they provide a more temporally precise and quantitative portrait of the actual corrosion phenomenon which allows for timely decisions and preventative measures.

4.2 Cover thickness

Using only point data makes it very difficult to analyze the effects of environmental parameters on specimen electrochemical behavior and particularly the effect of concrete cover thickness. However, cover thickness can be seen to have had an effect using the cumulative data (Figure 20-23); i_{accum} values behaved at different magnitudes in response to cover thickness. The accumulated corrosion rate, T and RH values confirmed that T and RH were closely linked inside the concrete matrix since they exhibited the same behavior and tendencies, independent of concrete fabrication method and quality. Although accumulated T and RH have no physical point meaning, their expression in this form aids in understanding their influence in degree of structure deterioration.

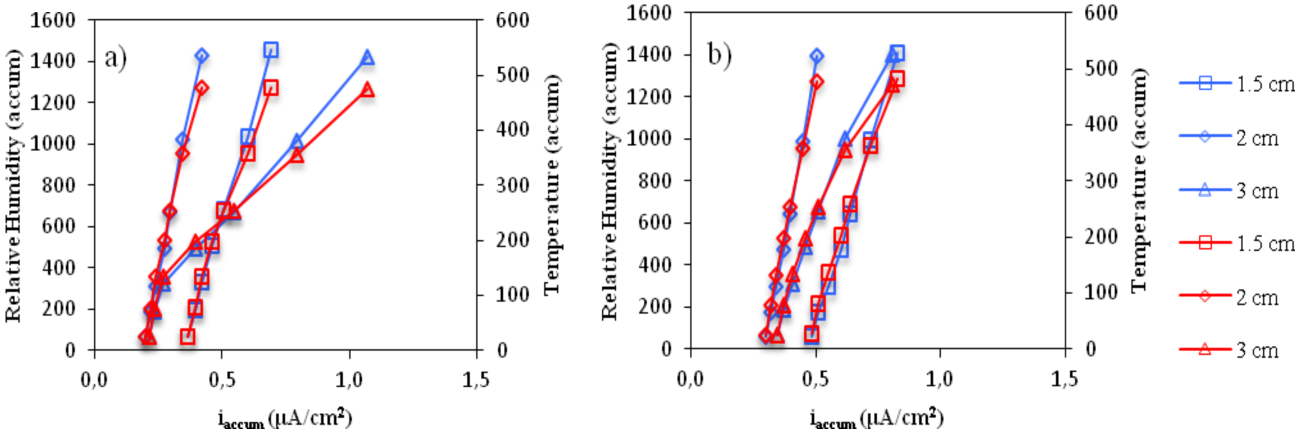


Figure 20. i_{accum} vs. T_{accum} and HR_{accum} for ACI specimens with w/c = 0.45: a) prevailing winds; b) non-prevailing winds.

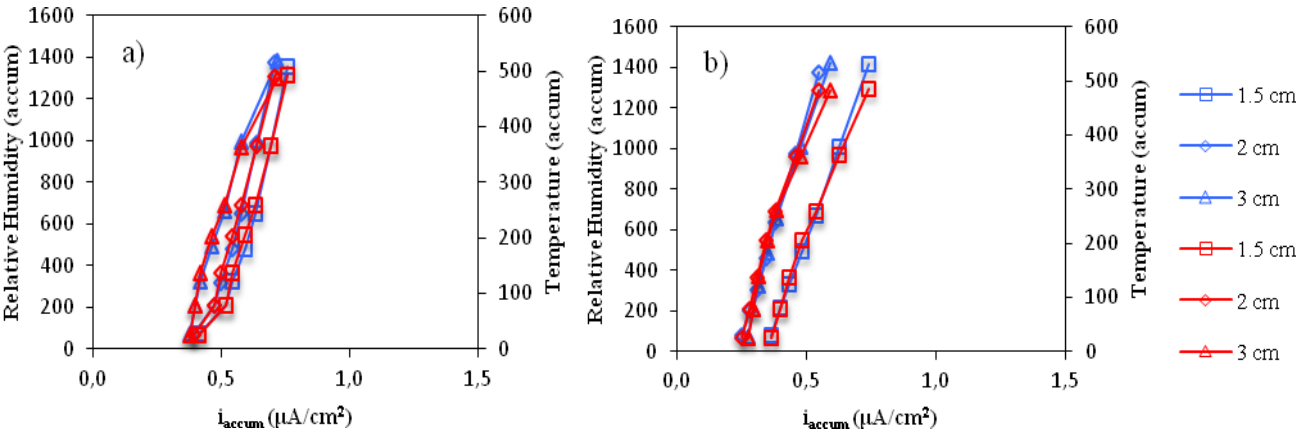


Figure 21. i_{accum} vs. T_{accum} and HR_{accum} for OM specimens with w/c = 0.45: a) prevailing winds; b) non-prevailing winds.

Analyzing the data in this way also showed that cover thickness had an unexpected effect. Normally, the deeper the steel reinforcement is within the concrete the lower its i_{accum} values when compared to those nearer the surface. However, the present data showed the contrary to be the case, a difference probably due to an edge effect in the exposed faces that allowed contaminants access along the lower edge, favoring moisture accumulation at three centimeters depth. This effect is most notable in the OM specimens with w/c = 0.65, which exhibited greater electrochemical activity in the reinforcement at three centimeters depth (Fig. 23). This can be attributed to its higher aggregate content, and moisture retention by the aggregate. In contrast, in the w/c = 0.45 specimens electrochemical activity was notably lower, with less activity in the OM specimens than in the ACI specimens (Figs. 20-21).

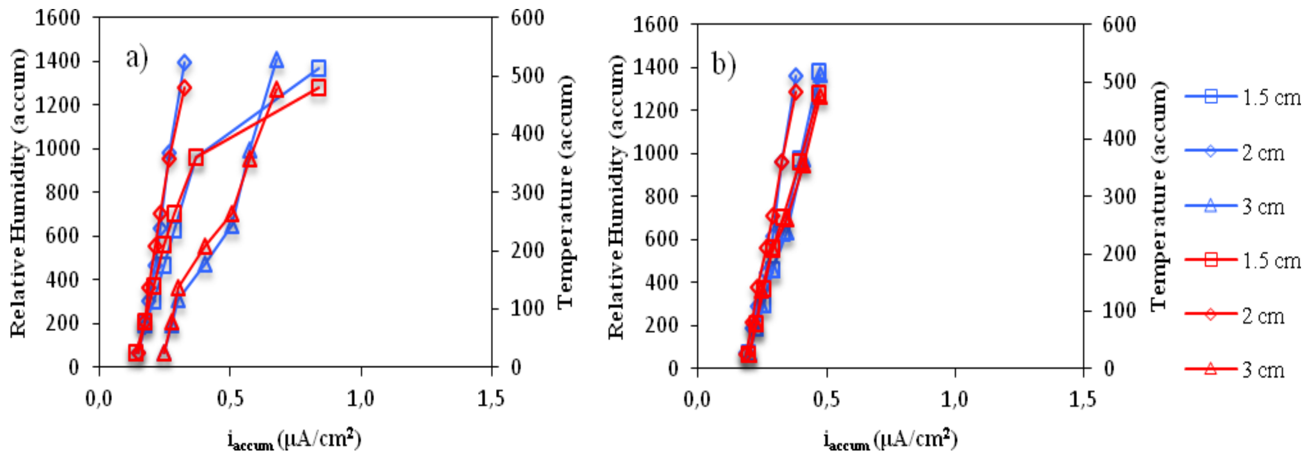


Figure 22. i_{accum} vs. T_{accum} and HR_{accum} for ACI specimens with w/c = 0.65: a) prevailing winds; b) non-prevailing winds.

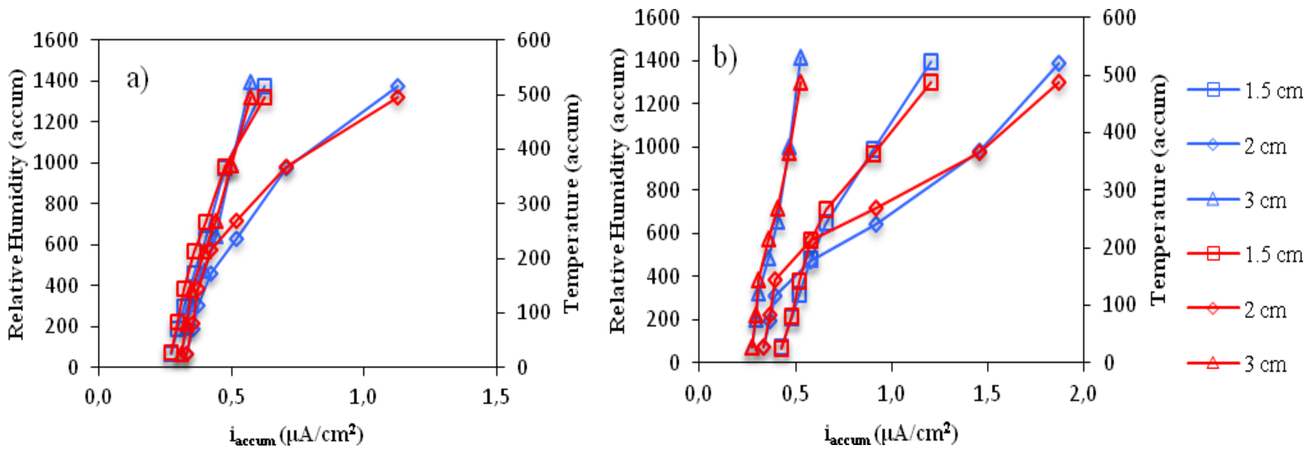


Figure 23. i_{accum} vs. T_{accum} and HR_{accum} for OM specimens with w/c = 0.65: a) prevailing winds; b) non-prevailing winds.

Although the exposure time used here is relatively short (24 months), the cumulative analysis identified some effects of the studied variables, such as orientation, cover thickness and concrete quality. These can seriously affect concrete service life over short periods but can be difficult to distinguish in a point analysis. At the end of the study period, all specimens remained in the passive values range (Figures 8-15). A certain tendency towards depassivation was noted but it was very difficult to determine the RH and T values needed to calculate corrosion activity as a function of steel reinforcement depth. Values varied constantly, which agrees with the observed behavior. Cumulative analysis was more effective at defining corrosion tendencies (Figures 20-23), and would therefore allow for more timely preventive measures. The specimens remain at the study site to allow for continued monitoring and evaluation. Generation of more data over a longer time span will help to extrapolate the data, and approximate the behavior of steel reinforcement in real structures.

Cumulative corrosion plots have been effective to show the beginning of depassivation through changes in the slopes of the data tendencies [16]. As was the case of this paper, other results from the literature could be reviewed in order to check the possible existence and meaning of such slopes. Boutiller Veronique, et.al. discussed in a previous paper [17] data from figures 24 and 25. Both plots correspond to instantaneous corrosion rates (Figs. 24 a) and 25 a)) from concrete cylinders (w/c ratios of 0.45 and 0.65) exposed to a chloride ingress through dry/wet cycles. Plots from both papers (Figs. 16-25) showed a similar behavior with expected fluctuations around the corrosion rate.

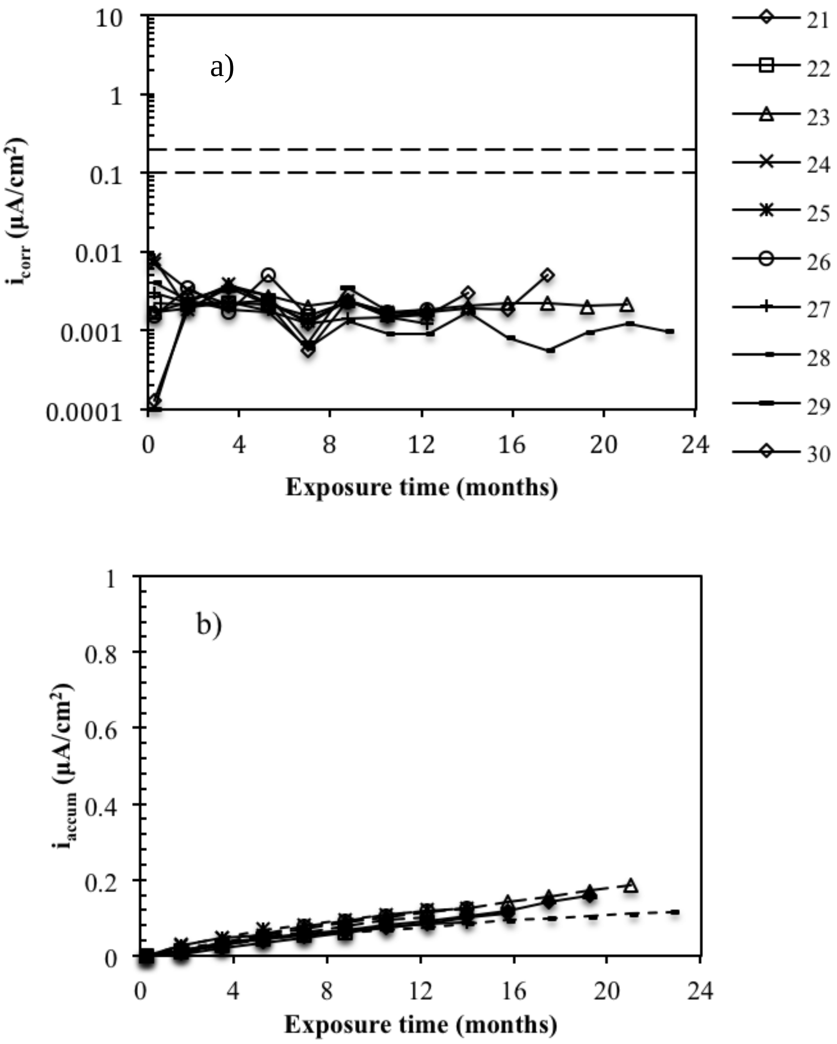


Figure 24. Graphs of a) Corrosion rate, b) accumulated corrosion rate, of cylinders with w/c = 0.45

Cumulative corrosion plots were drawn in figures 24 b) and 25 b). An expected lineality was observed for w/c ratio = 0.45. On the other hand curves from w/c ratio = 0.65 show a conservative behavior up to four months of exposure. After this period a significant change on the data slope was noted, indicating a certain tendency to depasivation. As observed, both groups of data, corresponding to different exposure conditions, methods of dossage, concrete quality, microclimates, geography and laboratories are showing clear slopes on the data at early ages, before depassivation. The analysis of the data slopes before depassivation of the reinforcement is then an adequate tool to extract corrosion information.

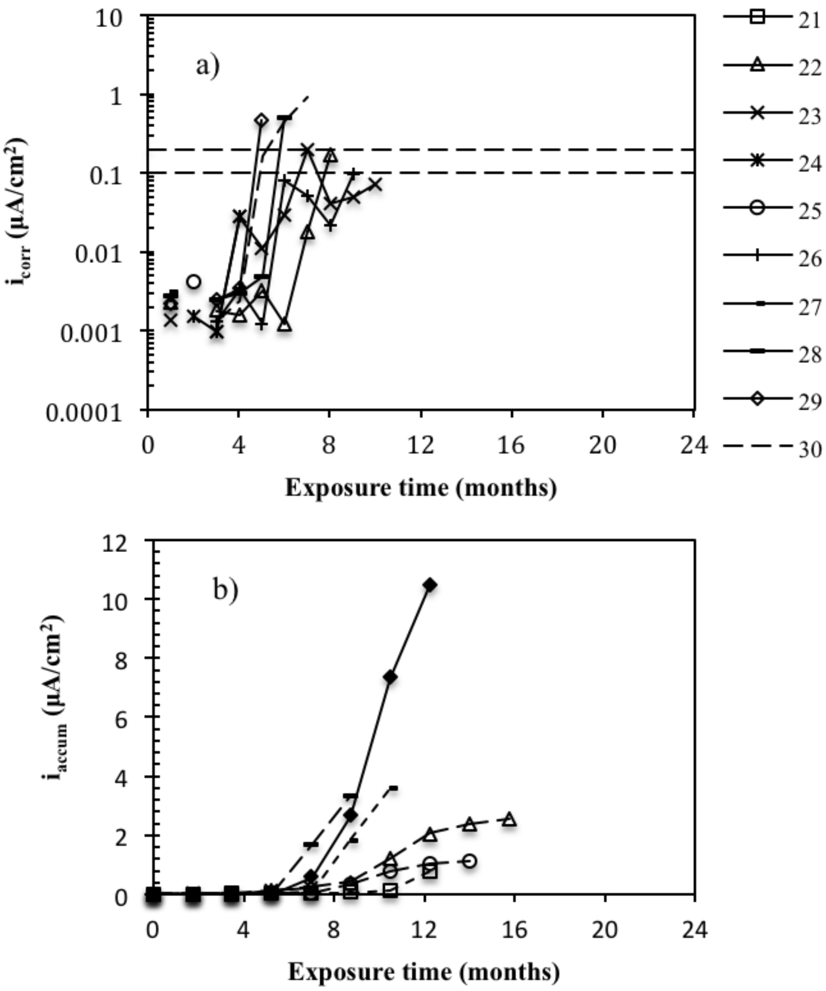


Figure 25. Graphs of a) Corrosion rate, b) accumulated corrosion rate, of cylinders with w/c = 0.65

5. CONCLUSIONS

After 24 months exposure in a tropical marine environment, concrete cover thickness was found to have no detectable influence on reinforcement despassivation. Nonetheless, the analytical tools discussed here did allow detection of edge effect durability problems. Aggregate proportioning was found to have a clear effect on electrochemical behavior under the studied conditions in that the low quality (w/c = 0.65) concrete specimens tended towards depassivation. Surface orientation towards the prevailing or non-prevailing winds had no apparent effect on electrochemical behavior, regardless of concrete design method. The analysis of the data slopes before depassivation of the reinforcement showed to be an adequate tool to extract corrosion information at early ages.

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