Corrosion Characterisation Of Reinforced Concrete Structures Exposed To Marine Environment

[1]Mohammad Ismail, [2]Hassan Ibrahim & Ogiri Thayalan Balakrishnan
Department of Structures and Materials
Faculty of Civil Engineering, Universiti Teknologi Malaysia
Johor, Malaysia
[1]mohammad@utm.my, [2]iohassan2@live.utm.my

Abstract— **One of the principal agents responsible for the degradation of reinforced concrete structures is the corrosion of the reinforcing rebar. In this study, the effects of chloride penetration as well as other degradation phenomenon on reinforced concrete structures in marine environment are being investigated. Field investigation was carried out using 2500mm×50mm×50mmreinforced concrete columns, produced from concrete grade 40 and 20 respectively. Three major tests, including half-cell potential, chloride content and carbonation depth were carried out at three different zones on the reinforced concrete columns corresponding to the atmospheric zone, tidal zone and submerged zone (zones A, B and C). Consequently, it was found that for both specimens, higher values of half-cell potentials, greater than .35V CSE were recorded in between 8-9 points in the submerged zones (corresponding to the lower tidal zone), while chloride ion content in the respective zones ranges between 0.17-0.28 with the highest values corresponding to the lower tidal zones. On the other hand, specimen A shows no evidence of carbonation while specimen B shows evidence of carbonation of up to 5mm in the lower tidal zone. Based on the findings, it is clear that the lower tidal zone has significant effect on corrosion and also has higher chloride content in comparism with other zones.**

Keywords- Corrosion; Degradation; Marine Environment; Reinforced Concrete; Carbonation; Half-Cell Potential; Chloride Content; Characterization

I. INTRODUCTION

Concrete as structural material is widely used in the construction of bridges, buildings, dams and marine structures such as concrete piers, decks, breakwater, retaining walls and jetties (Duffó, Reinoso, Ramos, & Farina, 2012). These structures are required to maintain their serviceability for a long period, sometimes up to 100 years. During this time, the structure should not lose its strength, functionability and aesthetic performance. Deterioration of concrete structures is the largest civil engineering challenge facing the developed world, because of its widespread occurrence in certain types of structures and the high cost associated with the repairs of these structures(Duffó, et al., 2012; Ismail, Siti Fatimah, & Muhammad, 2011; Shi, Xie, Fortune, & Gong, 2012). The principal cause of degradation of steel reinforced structures is corrosion damage to the rebar embedded in the concrete. Iron is unstable in nature, and because reinforcing steel used in reinforced concrete is made largely of iron, it, too becomes unstable when exposed to corrosive agents such as chloride from deicing salts, sea-water or from admixtures added during mixing, carbonation, humidity and even air(Mingawa & Hisada, 2008; Ustabas, 2012). The two most common causes of reinforcement corrosion are (i) localized breakdown of the passive film on the steel by chloride ions and (ii) general breakdown of passivity by neutralization of the concrete, predominantly by reaction with atmospheric carbon dioxide. Sound concrete is an ideal environment for steel but the increased use of deicing salts and the increased concentration of carbon dioxide in modern environments principally due to industrial pollution, has resulted in corrosion of the rebar becoming the primary causes of failure of this material(Ann, Pack, Hwang, Song, & Kim, 2010).

Oceans constitute 71-80% of the total earth surface, this entails that large number of civil infrastructures are exposed to sea water either directly or indirectly. This happens because wind carries seawater spray over a few miles from the coast to the inland structures. Furthermore, because of direct or indirect government policies aimed at relieving land from urban congestion and pollution, concrete made floating offshore platforms are now being used for offshore drilling platforms, oil storage tanks, power plants, airports and waste disposal facilities. The need therefore, to safeguard these infrastructures by fully understanding nature of concrete degradation in marine and coastal environment cannot be over emphasized. The most common approach to the investigation of the performance of reinforced concrete structures in marine environment is the assessment of its resistance to chloride ion penetration.

Previous investigations reported that the long term performance of concrete structures is basically a function of its deterioration level. Within the last decade, the number of reinforced concrete structures with deformities associated with reinforcement corrosion problem has increased tremendously, and this according to (Monteiro, Branco, Brito, & Neves, 2012) could be associated partly to concrete carbonation which occurs when carbon dioxide (CO2) penetrates into the concrete porous system to create an environment with lower PH around the reinforcement were corrosion progresses. On the other hand, the process could consist basically of electrochemical disintegration of the metal under an aggressive exposure condition, in which case, the steel reacts with mainly with oxygen and water to form hydrated iron oxides(cathodic or reduction reaction). In conjunction to this process, there is also an anodic or oxidation reaction, consisting of ion dissolution, accompanied by electrons transfer through the reinforcement to the cathodic zone(Richardson, 2002). To complete the electrochemical cell, the marine environment provides a good electrolyte for ion migration between anodic and cathodic areas(Page, 2007). Various techniques have been employed by previous researchers to evaluate the relative contribution of chloride diffusivity, carbonation, cathodic and anodic processes on the corrosion of steel reinforcement. Capacitance based embedded sensor was used in conjunction with portable SRI-CMIII half-cell tester to measure and calibrate corrosion potential (Ecorr) and corrosion rate (Icorr) parameters (Ismail, et al., 2011). In another research, Functional condition index (FCI) approach was used to calculate the condition index (CI) of marine structures, the data collected was used to evaluate corrosion of the reinforcement as well as cracking and spalling of concrete surface (Ayop, Zin, & Ismail, 2006). To study the corrosion durability of ferrocement, an electrochemical-based accelerated corrosion technique was employed. After suitable exposure, maximum crack width, percentage of steel loss and reduction in flexural strength were calculated and the tests results provided a good basis for assessing the relative performance of the ferrocement (Mansur, Maalej, & Ismail, 2008).

Although there are quite a number of studies on the corrosion of steel reinforcement in concrete, little work has been done on half-cell potential in conjunction with chloride depth and carbonation. The aim of this study was to evaluate the corrosion characteristics of reinforced concrete structures exposed to marine environment. Severity of the corrosion was determined through half-cell potential measurement, measurement of the chloride content and measurement of the carbonation depth.

I. EXPERIMENTAL

A. *Materials*

Ordinary Portland cement was used in conjunction with well graded fine and coarse aggregates and clean water was used for mixing. 12mm diameter high yield steel was used as reinforcement.

B. *Instrumentation*

The instrument used for the study include; a digital half-cell potential meter, concrete coring machine, universal strength testing machine, capillary tube, Vacuum saturation apparatus and phenolphthalein spraying pump.

C. *Specimen Preparation*

Two different concrete grades were produced with a target mean strength of 40MPa and 20MParespectively. Two different columns of dimensions 50mm×50mm×2500mm were cast from the two different concrete grades to represent specimens A and B. the two different specimens were reinforced with 12mm diameter high yield steel reinforcement. The concrete specimens were taken to the shore of a nearby ocean where they were properly fixed and tied to timber props and positioned in such a way as to replicate actual marine structures as shown in figure1.0. The specimens are demarcated into 3 different sections which correspond to the atmospheric, tidal and submerged zones. But because the specimens are positioned on the shore, the submerged region in this study was taken as the higher tidal zone. After the period of three months, the specimens were removed and the respective tests were carried out.

Figure1. Field experiment showing specimens and the respective zones

D. *Half-Cell Potential Mapping*

To effectively carry out this test, suitable points were marked on the three different zones of the respective specimens A and B. A digital half-cell potential meter was used to take measurements of the half-cell potential at each of the respective points as shown in figure 2.0.

Identify applicable sponsor/s here. If no sponsors, delete this text box. (Sponsors)

Figure2. (a-b) Half-cell potential measurement of specimens

E. *Determination of chloride content*

Concrete particles were obtained from atmospheric, higher tidal and lower tidal (submerged) zones as shown in figure 3.0. The ranges of chloride content in the concrete specimens by weight of the concrete dust extracted using capillary tube from the respective zones were determined.

Figure3. Concrete particles from different zones for chloride content determination.

F. *Concrete carbonation test*

For the carbonation test, 25mm core samples were taken from the respective zones of the Concrete Specimens. The concrete cones were split, using the universal strength testing machine and the freshly exposed surfaces of the concrete specimens were sprayed with a 1% phenolphthalein solution and monitored (see figure 4.0). Changes were then observed and recorded.

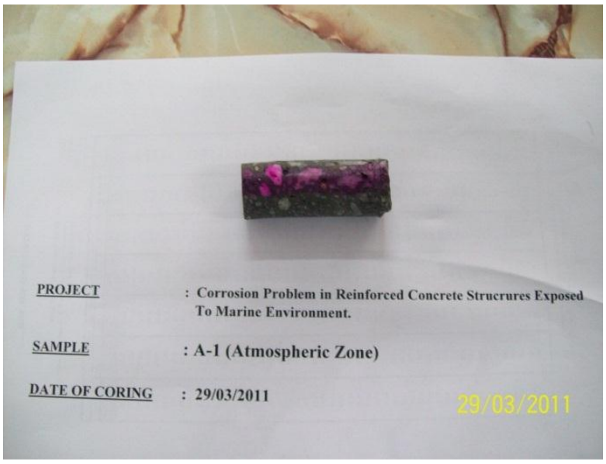

Figure4. Sprayed samples for carbonation test obtained from specimen A

Figure5. Sprayed samples for carbonation test obtained from specimen B.

II. RESULTS AND DISCUSSIONS

G. *Half Cell Potential Mapping*

The Half – Cell Potential measurement for specimen A shows that readings from 3 points out of the 4 points in atmospheric zone indicate that corrosion activity of the reinforcing steel in the areas are uncertain. Reading from the remaining point in the atmospheric zone is > -0.35 V CSE, indicating a strong probability that reinforcing steel corrosion is occurring in that area at the time of measurement.

A total number of 11 points were mapped in the higher tidal zone and the results shows that 9 points indicated half-cell potential readings ranging between -0.20 to -0.35 V CSE, which is an indication of uncertainty that corrosion activity is taken place in that area on the other hand, 2 points within the same zone presented values greater than -0.35 V CSE, this entails that there is 90% certainty that reinforcement corrosion is taken place. Results of 8 points considered in the lower tidal (submerged) zone, shows values greater than -0.35 V CSE.

On comparative basis, half-cell potential measurement on concrete specimen B shows that all the points taken in each of the respective zones, have values greater than -0.35 V CSE, which is an indication of strong probability that the reinforcement embed in the specimen is corroding. Refer to tables 1.0 and 2.0.

TABLE I: SUMMARY OF HALF CELL POTENTIAL MEASUREMENT FOR CONCRETE SPECIMEN A.

Specimen Type A : Concrete Grade 40			
Location	No. of Point from Cumulative Frequency Diagram		
	< -0.20 V CSE	-0.20 to -0.35 V CSE	> -0.35 V CSE
A-1 (Atmospheric Zone)	-	3points identified	1point identified
A-2 (Higher Tidal Zone)	-	9points identified	2points identified
A3(Lower tidal/Submerged Zone)	-	0 point identified	8points identified
Remarks: i) Less than -0.2 V CSE, there is greater than 90% probability that no reinforcing Steel corrosion is occurring. ii) Range of -0.20 to -0.35 V CSE, corrosion activity of the reinforcing steel in that Area is uncertain. iii) Greater than -0.35 V CSE, there is greater than 90% probability that reinforcing Steel corrosion is occurring.			

TABLE II: SUMMARY OF HALF CELL POTENTIAL MEASUREMENT FOR CONCRETE SPECIMEN B.

Specimen Type B : Concrete Grade 20			
Location	No. of Point from Cumulative Frequency Diagram		
	< -0.20 V CSE	-0.20 to -0.35 V CSE	> -0.35 V CSE
B-1 (Atmospheric Zone)	-	-	3point identified
B-2 (Higher Tidal Zone)	-	-	7points identified
B-3(Lower tidal/Submerged Zone)	-	-	9points identified
Remarks: i) Less than -0.2 V CSE, there is greater than 90% probability that no reinforcing Steel corrosion is occurring. ii) Range of -0.20 to -0.35 V CSE, corrosion activity of the reinforcing steel in that Area is uncertain. iii) Greater than -0.35 V CSE, there is greater than 90% probability that reinforcing Steel corrosion is occurring.			

B. *Chloride content*

The results of chloride content are tabulated in table 3.0 and 4.0 respectively. The concrete dust samples were extracted from atmospheric, higher tidal and lower tidal (submerged) zones using capillary tubes.

The range of chloride content in the Concrete Specimen A, by weight of dust in atmospheric zone was 0.17%, higher tidal zone was 0.21% and the chloride content in higher tidal (submerged) zone was 0.21%. On the other hand, for concrete specimen B, the range of 0.24% Chloride content was identified at Atmospheric Zone. In the lower tidal zone, the amount of chloride content found was 0.26% by the weight of extracted sample and for lower tidal (submerged) zone, 0.28% Chloride Content was analyzed. The results shows that the rate of chloride diffusivity seems to progress more rapidly in the across all zones in the specimen B (concrete grade 20) than in specimen A (concrete grade 40). It can be observed that the tidal zone in the experiment have a significant effect on corrosion due to regular wetting and drying with the associated more with the lower Grade of concrete (specimen B) compared to concrete specimen A. In fact, in many cases, it constitutes the predominant cause of corrosion of the reinforcement. As mentioned earlier, the chloride reaction in concrete is directly dependent on the condition under which the concrete structure is exposed to. The tidal zone, between the levels of high and low tides, is subjected to the regular wetting and drying. This wet/dry cycle results in the regular saturation of the concrete with saltwater which then may evaporate as the tide ebbs.

The result also indicates that with continuous exposure beyond the period of this experiment, the threshold of 0.40 required for aggressive chloride corrosion will be reached, particularly for specimen B.

TABLE III: CHLORIDE CONTENT (CI) EXPRESSED IN % BY WEIGHT OF CONCRETE DUST FOR SPECIMEN A

Location	Chloride Content (Cl, %)
A-1 (Atmospheric Zone)	0.17
A-2 (Tidal Zone)	0.21
A-3 (Submerged Zone)	0.27
Remarks: Reinforcement corrosion can be proceeding more actively with chloride concentration above 0.4% by weight of cement in the concrete	

TABLE IV: CHLORIDE CONTENT (CI) EXPRESSED IN % BY WEIGHT OF CONCRETE DUST FOR SPECIMEN B

Location	Chloride Content (Cl, %)
B-1 (Atmospheric Zone)	0.24
B-2 (Tidal Zone)	0.26
B-3 (Submerged Zone)	0.28
Remarks: Reinforcement corrosion can be proceeding more actively with chloride concentration above 0.4% by weight of cement in the concrete	

C. Concrete Carbonation

Carbonation results (as shown in tables 5.0 and 6.0) were determined by spraying a freshly exposed surface of the concrete with a 1% phenolphthalein solution. The carbonation test results indicated that no any active carbonation activity has taken place on both the internal and external surfaces of samples from specimen A, obtained from the three zones. However, the core samples taken from concrete specimen B indicates that carbonation has taken place in the lower tidal (submerged) zone, to a depth of up to 5mm. The pH value has also changed from 13 to 7.

TABLE V: CARBONATION RESULT FOR CONCRETE SPECIMEN A

Specimen	Diameter (mm)	Marking	Depth of Carbonation, (mm)	
			Internal Face	External Face
A	25	Atmospheric Zone	None Detected	None Detected
	25	Higher Tidal Zone	None Detected	None Detected
	25	Lower tidal (Submerged) Zone	None Detected	None Detected

TABLE V1: CARBONATION RESULT FOR CONCRETE SPECIMEN B

Specimen	Diameter (mm)	Marking	Depth of Carbonation, (mm)	
			Internal Face	External Face
B	25	Atmospheric Zone	None Detected	None Detected
	25	Higher Tidal Zone	None Detected	None Detected
	25	Lower tidal (Submerged) Zone	None Detected	None Detected

Conclusion

Based on this present study, it has been further confirmed that the environment (temperature) plays a very important role in the corrosion of steel reinforcement. Half-Cell potential mapping and measurement shows that concrete specimen B presented higher number of points within the higher tidal zone and lower tidal (submerged) zone, which is an indication of increasing probability of corrosion. The measurements obtained from these points were greater than -0.35 V CSE. From this zone, the highest ranges of chloride content were also obtained ranging, from 0.26% to 0.28% with an average of 0.27%. As we noted in the tidal zone, the corrosion potential and the corrosion rate show a linear rise with the increase of chloride content in the specimen. From this experiments and results, it can be concluded that, the result of wetting and drying speeds up the ingress of chlorides into the concrete and cause the corrosion of steel reinforcing bars embedded inside the concrete. Generally cement paste has a pH of about 13 which provides a protective layer (passive coating) to the steel reinforcement against corrosion. Consequently, concrete specimen B at the lower tidal (submerged) zone exhibited a lower pH value of 7 with an associated 5mm depth of Carbonation detected from the external face.

It therefore important to note at this juncture that, corrosion is the final result of all forms of deterioration which may be initiated from the inside, when the materials of the concrete contains impurities or from the outside when the concrete has high permeability.

REFERENCES

JOURNAL:

Ann, K. Y., Pack, S. W., Hwang, J. P., Song, H. W., & Kim, S. H. (2010). Service life prediction of a concrete bridge structure subjected to carbonation. *Construction and Building Materials, 24*(8), 1494-1501.

Ayop, S. S., Zin, R. M., & Ismail, M. (2006). Condition assessment of marine structures using functional condition index approach. *Malaysian Journal of Civil Engineering, 18*(2), 129-138.

Duffó, G. S., Reinoso, M., Ramos, C. P., & Farina, S. B. (2012). Characterization of steel rebars embedded in a 70-year old concrete structure. *Cement and Concrete Research, 42*(1), 111-117.

Ismail, M., Siti Fatimah, A. R., & Muhammad, B. (2011). Embeded Sensor for Detecting Corrosion of Reinforcement in Concrete. *Advanced Material Research, 250-253,* 1118-1123.

Mansur, M. A., Maalej, M., & Ismail, M. (2008). Study on Corrosion Durability of Ferrocement. *ACI Materials Journal, 105*(M04), 28-34.

Mingawa, H., & Hisada, M. (2008). Influence of content and origin of chloride ion on repairing effect of desalination method. *Proceedings of the 3rd ACF International Conference-ACF/VCA, , Ho Chin Minh City, Vietnam.*Vietnam Institute for Building Materials,Hanoi.Vietnam, 1041-1047

Monteiro, I., Branco, F. A., Brito, J. d., & Neves, R. (2012). Statistical analysis of the carbonation coefficient in open air concrete structures. *Construction and Building Materials, 29*(0), 263-269.

Richardson, M. G. (2002). *Foundamentals of durable reinforced concrete*. Britain: Spon Press.

Shi, X., Xie, N., Fortune, K., & Gong, J. (2012). Durability of steel reinforced concrete in chloride environments: An overview. *Construction and Building Materials, 30*(0), 125-138.

Ustabas, I. (2012). The effect of capillarity on chloride transport and the prediction of the accumulation region of chloride in concretes with reinforcement corrosion. *Construction and Building Materials, 28*(1), 640-647.

Books:

Page, C. L. (2007). Corrosion and protection of reinforcing steel in concrete *Durability of Concrete and Cement Composites* (pp. 136). Cambridge: Woodhead and Maney.