Effect Of Age And Concrete Cover Thickness On Steel Reinforcement Corrosion At Splash Zone In Reinforced Concrete Hydraulic Structures

Nada M. Al- Galawi, Ali A. H. Al-Tameemi, Sarah H. Al-Jarrah

Abstract— Corrosion of reinforcing steel bars in reinforced concrete is considered as one of the biggest problems that face countries overlooking to the Arabian Gulf, including Iraq. The research aims to study the effect of the corrosion of steel bars in concrete structures that are exposed to wetting and drying via waves. Reinforced concrete samples were exposed to marine simulated environment for 90 days using prepared system for this purpose. At the end of exposure period, polarization test was implemented to measure the actual corrosion rate in each sample. After that, the corrosion process was accelerated using "impressed current technique" by applying a constant electric current (DC) to the reinforcing bars. Depending on the corrosion current in natural conditions which was measured in polarization test, periods of exposing samples to accelerated corrosion current so as to maintain virtual exposure ages of 5 and 25 years of exposure to natural corrosion, were calculated. The results showed a remarkable increase in the corrosion current of steel bars in samples that had lower concrete cover thickness. The increase in the cover thickness from 20mm to 40 and 65 mm had a significant effect on reducing the corrosion current at the age of 90 days to about 70% of its original value, in both cases. At the virtual exposure age of 5 years, the reduction percentage in the corrosion current resulted from increasing cover thickness from 20mm to 40 and 65 mm were 43% and 79 % respectively.

Index Terms— Corrosion, hydraulic structure, splash zone, concrete cover, virtual exposure age, marine simulated environment

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1 INTRODUCTION

Corrosion of reinforcing steel is one of the most important and prevalent mechanisms of deterioration for reinforced concrete structures in marine environment. About 95% from the concrete damages in the Arabian countries shores in Gulf region are resulted from corrosion that leads to cracking in the concrete cover of reinforced bars [1]. The marine environmental conditions which are characterized with high sulfates, high concentration of chlorides, high temperature, and relative humidity are considered as accelerating factors for the corrosion of steel reinforcement. The difference in temperature on the earth's surface and change of atmospheric pressure usually generate the wind. Movement of wind by surface of the seas and oceans leads to the movement of surface water molecules causing formation of waves. The waves cause alternate wetting and drying at the body of structure exposed to the marine environment. Therefore, the parameters of corrosion, which includes of oxygen, water, and chloride, are concurrent at the same time causing accelerated corrosion processes [2,3]. Severe corrosion degree of steel reinforcement causes wide cracks and spalling of concrete cover. The depth of the concrete cover plays an important role in protection of reinforcement in concrete. The cover thickness has a remarkable effect on rebar corrosion due to penetration of chloride or carbonation [4]. **Mohammed et al. 2011** [5] show that the effect of increase in cover thickness was less important for the severe corrosion level.

The main aim of the research is to study the effect of age and concrete cover on the electro-chemical behavior of the reinforcing bars in marine concrete structures, exposed to wetting and drying at the splash zone. Information about corrosion current and corrosion potential during exposure periods will give an idea about the effect of variation of age and concrete cover on the rebar corrosion beside the behavior of reinforced concrete exposed to marine environment.

2. Details of the tested specimens

Tested specimens were reinforced concrete prisms with different dimension. The specimens were exposed to water from two sides where steel reinforcement was placed at a distance from each face equal to concrete cover normally employed in construction. Dimensions of specimens with different cover thickness to fulfill the above requirement are shown in figure (1). This configuration was chosen to represent the most expected sever exposure condition for rebars in marine environment.

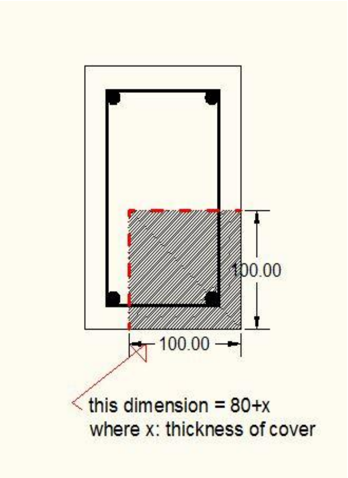

Figure 1: Details of reinforcement and concrete dimension for reinforced concrete specimens

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Concrete mixes for 28MPa compressive strength was designed in accordance with American Concrete Institute (ACI- 211) [6] method in the current study. The mix proportions were (1:1.5:2.46) (w/c, cement, fine aggregate, coarse aggregate) respectively. Water cement ratio of 0.48 for this mix was chosen depending on the limitations of Iraqi building code [7] for concrete exposed to sea water. Table (1) shows the designation of specimens, dimensions, thickness of concrete cover, and number of specimens.

Table (1): The designation and details of tested specimens

designation of specimens	**Dimensions mm*mm**	**Cover thickness (mm)**	**Number of specimen**
R28-20	**100*100**	**20**	**4**
R28-40	**120*120**	**40**	**4**
R28-65	**150*150**	**65**	**4**

3. Exposure conditions

Specimens were exposed to saline water waves similar to those waves encountered in sea environment for 90 days. Tidal zone and splash zone were created via a new invented system. The concentration of chloride ion in water used in the current study was 3.5%, whereas the sulfate content was 0.55%. The temperature was between "25-40"°C.

4. The Accelerated corrosion Program:

When the period of exposure to marine simulated environment ended, electrochemical tests had been carried out in order to detect the corrosion current in reinforced bars. Depending on this current, rebars corrosion had been accelerated so as to attain virtual exposure ages of 5 and 25 years of exposure to natural corrosion. Corrosion was intended to take place in rebars at predetermined portions of the reinforced concrete specimens. "The impressed current technique" had been applied to accelerate the reinforcing steel corrosion. To provide the required impressed current for rebars corrosion, 30V, 3A constant current D.C power supply devices were used. Each power supply device included two poles, positive poles in the circuits were connected to the reinforcing bars (working as anodes); while stainless steel sheets were connected to the negative poles (working as cathodes). The electric connection of stainless steel sheets and rebars to the D.C. circuit was tight as the electric wires were well connected to a small hole in the stainless steel sheets, using a terminals device. The electric conductivity between concrete surface and stainless steel sheets was enhanced by using wet burlaps; wetted continuously by water dripping system proposed by Al-Tamimi [8].

5. Results

Results are analyzed and discussed to study the effect of age and the thickness of concrete cover on the behavior of reinforced concrete members subject to corrosion of steel reinforcement in an environment similar to marine environment.

5.1 Polarization measurements

The polarization test was made for all specimens after 90 days of exposure to the marine simulated environment. The value of the corrosion current density was depended in the process of accelerating corrosion current to attain virtual exposure ages of 5 and 25 years of exposure to natural corrosion. Then, the polarization measurements were taken for all specimens after reaching the required ages. The results of the polarization test for steel bars embedded in different prisms showed that there was a significant increase in corrosion current density with time. This trend of increase in corrosion current density was not similar. The effect of age in some rebars was slight, and in other bars was significant. Corrosion current density for all tested specimens is shown in Table (2).

Table (2): corrosion current density at the different ages for all tested specimens

Sample	I_{corr} (μA)			i_{corr} = I/A ($\mu A/cm^2$)		
	90 Days	1825 days	9125 days	90 Days	1825 days	9125 days
R28-20	18.61	32.47	-	0.209	0.364	-
R28-40	6.3	18.42	95.17	0.058	0.170	0.879
R28-65	5.95	6.88	18.42	0.059	0.068	0.183

5.1.1 Effect of age on corrosion of rebars with 20 mm cover thickness

Figure (2) shows the progress of corrosion current density for bars embedded in sample (R28-20), with 20 mm cover thickness. After 90 days of exposure to marine simulated environment, the corrosion current density reached (0.209μA/cm^2) for steel bars embedded in prisms (R28-20), whilst, after accelerating of corrosion current in the same rebar for virtual exposure age of 5 years the corrosion current density was increased to (0.364μA/cm^2). This means that the percentage of increase in the corrosion current density for this rebar after virtual exposure ages of 5 years is 74% with respect to the age of 90 days. Although large increase in corrosion current density at this bar, but it did not pass the “Low” limit of corrosion rate. This indicated a slowly progress of the corrosion current at the early ages of hydraulic structure exposed to marine environment. After attending a virtual exposure age of 25 years there was a high damage in the concrete cover of the same sample with 28 MPa concrete. The reason for this could be due to the high degree of corrosion in the rebar which led to increasing of the rebar size. Therefore, the corrosion current density value of the bar had been lost. These two cases may be attributed to the small cover thickness, which may indicate a high risk upon using of this cover thickness in the marine structure.

5.1.2 Effect of age on corrosion of rebars with 40 mm cover thickness

Figure (3) shows the progress of the corrosion current density for steel bars in sample that had 40mm cover thickness. This figure shows that the corrosion current density of rebar in sample (R28-40) was (0.058 μA/cm^2) after 90 days of exposure to marine simulated environment. For the same bar, after accelerating corrosion to virtual exposure age of 5 years and 25 years the value of corrosion current density (0.170μA/cm^2) and (0.879μA/cm^2) respectively. However, the corrosion rate reached “negligible” level after 90 days of exposure, and ranged from “low” to “moderate” levels after virtual exposure age of 5 years, 25 years respectively. So, using of cover thickness (40mm) according to Arabian code may exposes the hydraulic structure in marine environment to considerable corrosion risk after 25 years or more.

5.1.3 Effect of age on corrosion of rebars with 65 mm cover thickness

The cover thickness of 65 mm is specified by ACI- 357 [9] for reinforced concrete in marine structure, exposed to cycles of wetting and drying within the marine environment structures. The results of the polarization test for samples with 65mm cover thickness indicated a decrease in corrosion current density in the bars embedded in those samples, compared to bars embedded in sample that have 20mm and 40mm cover thickness. For the steel bar embedded in sample (R28-65) the corrosion current density was 0.059μA/cm^2 after 90 days of exposure to marine simulated environment. Whilst, after accelerated of corrosion current to virtual exposure age of 5 years, the corrosion current density was 0.068μA/cm^2. Consequently, the percentage of increase in the corrosion current density due to 5 years of exposure to marine environment was 15%. Although corrosion was accelerated to virtual exposure age of 5 years, but, the corrosion rate did not exceed the “negligible” limit according to ACI-222 [10]. Likewise, at the virtual exposure age of 25 years the corrosion current density for steel bars in sample (R28-65) was 0.183μA/cm^2, leading to an increase of about (200) % in comparison with corrosion current density at the age of 90 days, as shown in figure (4). The corrosion rate stayed in the "low" limit after accelerating corrosion current to virtual exposure age of 25 years.

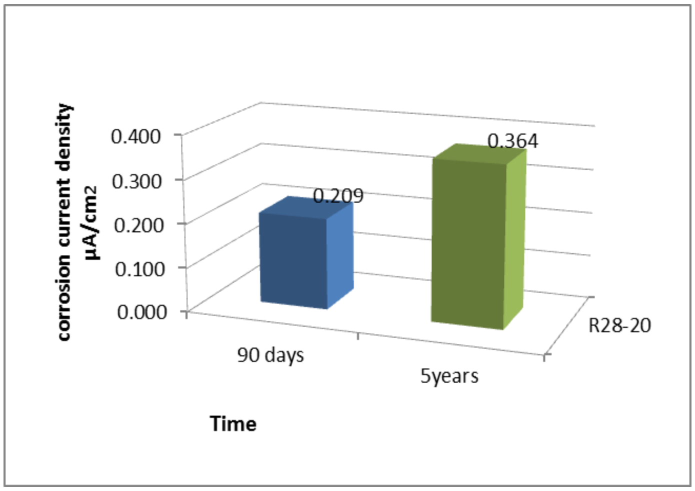

Figure (2): development of corrosion current density for steel bars embedded in sample (R28-20) with time.

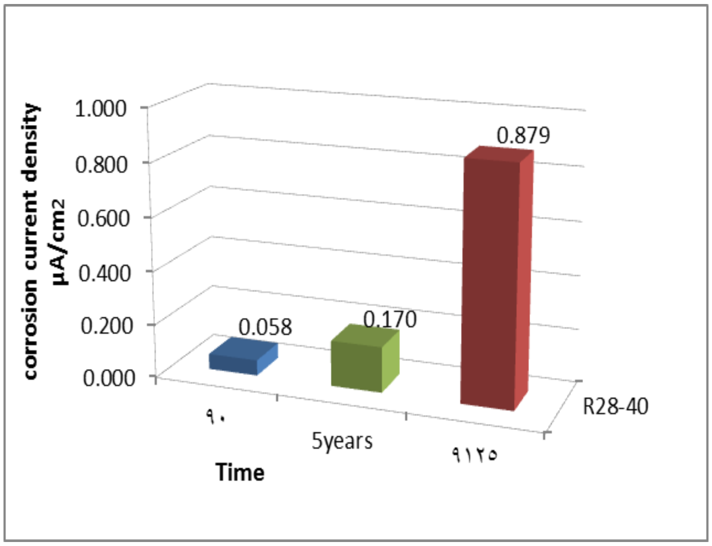

Figure (3): development of corrosion current density for steel bars embedded in sample (R28-40) with time.

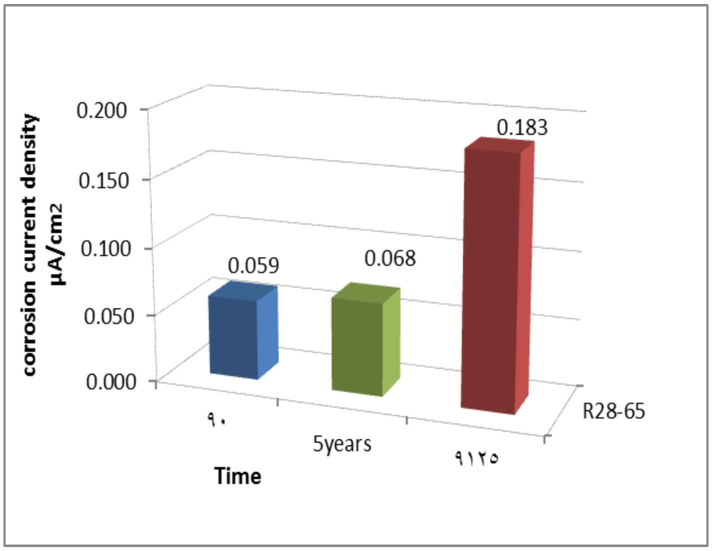

Figure (4): development of corrosion current density for steel bars embedded in sample (R28-65) with time.

5.2 Effect of increasing the cover thickness on the corrosion current density

Figure (5) shows the corrosion current density of steel bars in prisms that had different cover thickness for different ages. Steel bars which had been tested after 90 days of exposure to the marine simulated environment had shown excellent reduction in the corrosion current due to increasing cover thickness. As shown in table (2), for 28MPa concrete, the corrosion current density of the rebar in specimens that had 20 mm cover thickness (R28-20) at the age of 90 days was 0.209 $\mu A/cm^2$, while, the corrosion current densities were 0.058$\mu A/cm^2$ and 0.059$\mu A/cm^2$ in the rebars embedded in specimens that had 40 and 65 mm cover thickness respectively. Consequently, the increase of cover thickness to 40mm and 65mm reduces the corrosion current at same percentage, it was 71% approximately. At the virtual exposure age of 5 years, the corrosion current density of rebars in the sample R28-20 was 0.364 $\mu A/cm^2$. While, the corrosion current density for the steel bars embedded in samples R28-40 and R28-65 were 0.170$\mu A/cm^2$ and 0.068 respectively. The reduction in corrosion current is (43%) due to doubling of cover thickness, and (79%) due to tripling of concrete cover thickness. However, the corrosion rate had been changed from "low" to "negligible" when the cover thickness was increased to 65mm. Obviously, increasing the cover thickness leads to increase in the path that the chloride ions must pass through to reach the reinforced steel that is embedded in concrete. Therefore, increasing the cover thickness delays the occurrence of the corrosion. At the virtual exposure age of 25 years, the corrosion current value of the rebars in sample R28-20 had been lost due to the deep cracks in the concrete cover. Therefore, comparison was done between only cases of increasing cover thickness from 40 mm to 65mm. As shown in figure (5), the percentage of reduction in the corrosion current density was (79)%, when the cover thickness was increased from 40mm to 65 mm.

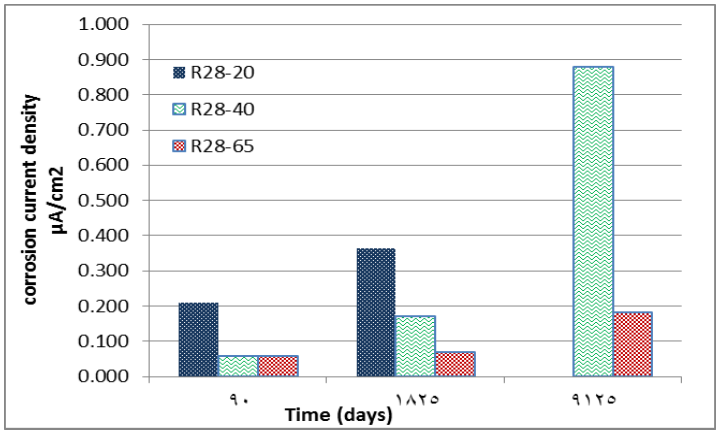

Figure (5): Effect of increasing cover thickness on corrosion current density of steel bars embedded in specimens that have 28MPa compressive strength with time.

6. Half Cell Potential results (HCP)

The results had shown more positive values in the potential for the specimens that have a larger cover, compared with specimens that have a lower cover thickness. Table 4 shows the results of half-cell potential test during marine simulated environment. Figure (8) shows the progress of half-cell potential with time of exposure for specimens that had compressive strength of 28 MPa and which have different thickness of cover. This figure shows that doubling cover thickness led to a change in the potential to about (18) % after 90 days of exposure. However, tripling thickness of cover led to 15% and 14 % change after 40 and 90 days of exposure respectively.

Table (4): results of half-cell potential test during marine simulated environment

Specimens	half-cell potential (mv) values after:		
	3days	40 days	90 days
R28-20	553	424	329
R28-40	520	419	388
R28-65	529	448	374

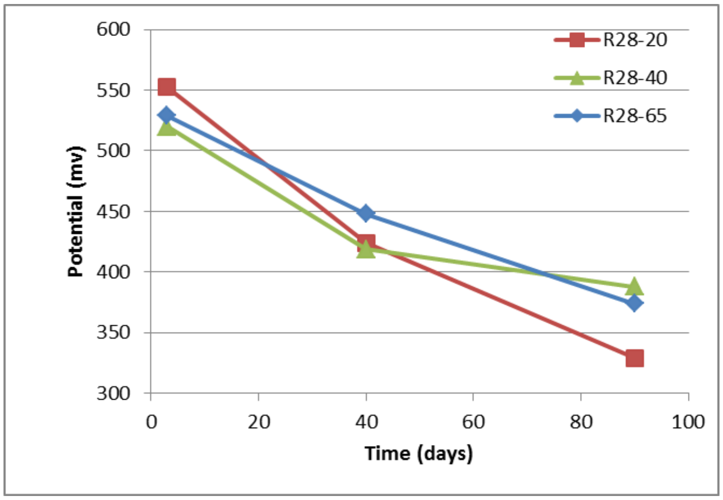

Figure (8): Effect of increasing cover thickness; on HCP of the bars during 90 days of exposure to marine simulated environment.

Test results of the half-cell potential after acceleration of corrosion to virtual exposure ages of 5, 15, 25 years are shown in table (5). The half-cell potential of all specimens exposed to accelerated corrosion program showed negative values. However, the potential of bars showed was between intermediate and high risk of corrosion, according to ASTM C876 [11]. These results indicate that the protective film was destroyed. However, at the virtual exposure age of 5 years, a sharp decrease in half-cell potential for all mixtures had been noticed compared with the value of half-cell potential at the age of 90 days.

6.1 Effect of increasing thickness of concrete cover after accelerated corrosion process

Increasing thickness of concrete cover had a significant impact on the value of potential through the period of exposure to marine simulated environment. This behavior continued during the accelerated corrosion stage. Figure (9) shows the variation of HCP due to the increase in the thickness of concrete cover. At the virtual exposure age of 5 years, increasing thickness of cover to 40 mm changed the rebars potential from -503.5 to -370 mv, therefore the change in HCP was 27%; while increasing the thickness of cover to 65 led to less negative value of HCP, it was -309 mv and the change percentage was 39%. At the virtual exposure age of 15 years. HCP of bars in prism R28-20 was -653 mv and HCP of bars in prism R28-40 was -553mv. This means that the change in potential was 11%. Moreover, when increasing the thickness of the cover to 65 mm, there was sharp changed in potential reached 49%. As shown in table 5, and figure (9), the change in HCP of bars at the virtual exposure age of 25 years were 28% and 47% due to increasing cover thickness to 40 and 65 mm respectively.

Table (5): Half-cell potential result of accelerating corrosion stages

Specimens	The value of half-cell potential after accelerated corrosion to (day):		
	1825	5475	9125
R28-20	-503.5	-653	-702
R28-40	-370	-553	-506
R28-65	-309	-337	-369

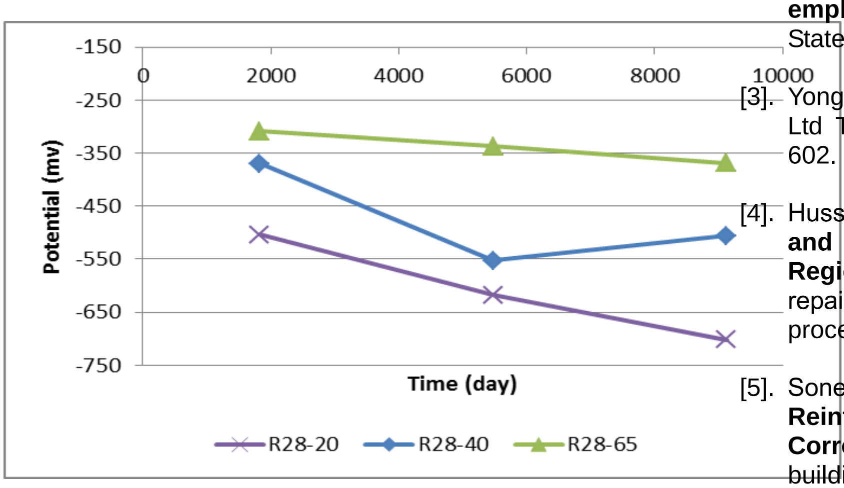

Figure (9): Effect of thickness of cover on potential of bars at acceleration corrosion stage.

7. Conclusions

- Progress of corrosion current was seen to be related to thickness of the concrete cover. High values of corrosion current were noticed in samples with 20 and 40 mm cover thickness; while lower values were recorded in samples with 65mm cover thickness.
- Corrosion current in reinforced concrete samples exposed to marine simulated environment was progress at slow rate after few years of virtual exposure up to 5 years. However, high increase in corrosion current was recorded after virtual exposure period of 25 years, that led to severe cracking of concrete cover in samples with 20 mm cover thickness.
- The corrosion current density of reinforcing bars that had cover thickness within the limits specified by universal codes led to a negligiable corrosion rate after 90 days of exposure to marine simulated environment.
- The reduction in corrosion current density was 60% due to increasing the cover thickness from 40mm to 65mm (R28-40 and R28-65) at the virtual exposure age of 5 years. But at the virtual exposure age of 25 years of exposure, highest reduction in corrosion current density was recorded; it was 91% for same specimens mentioned above.
- After 90 days of exposure to marine simulated environment the results showed more positive values in HCP for the specimens that have larger concrete covers.
- After virtual exposure age of 5 years, increasing thickness of cover from 20mm to 40 mm and 65 mm changed HCP of bars by 27% and 39% of the original value respectively.
- The changes in HCP of bars after virtual exposure age of 25 years were 28% and 47% due to increasing cover thickness from 20mm to 40 and 65 mm respectively.

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