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A Review on Corrosion of Reinforcing steel in Concrete Structures Located on the Southern Coast of Iran

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ABSTRACT ─ Coastal Structures in the Middle East are influenced by hydrostatic pressure, impact loading, erosion and continuous cycles of changes in temperatures. As a result, these structures are often made of high strength concrete and reinforcement steel. Therefore, protecting steel embedded in concrete is critical from the point of view of durability. Concrete permeability is the most important determinant of long-term durability. Although concrete is considered as a durable material in the marine environment, many collapses have been reported from concrete structures by the beach. The durability of the material can be resulted from the proper implementation and maintenance. The situation of the Persian Gulf in terms of salts in seawater and in terms of its climatic conditions have made this environment as one of the most aggressive marine environments from the perspective of corrosion of reinforcement in concrete structures. Early collapses due to corrosion of reinforcement in concrete structures in the Persian Gulf region have caused a lot of maintenance costs for countries in this region. Therefore, the increasing tendency to determine the causes of the corruption in concrete, the methods to prevent it, and contributing factors in high resistance and strength, unlike the short life of the concrete, is a sign for the importance of the issue. In this study, a number of samples with water-cement ratio of 0.45 to 0.5 are provided to investigate the damage to reinforced concrete structures due to corrosion of rebar. They are tested after being submerged in different atmospheric, splash and tidal zones. Then, chloride penetration, electrical resistance, potentials and corrosion current strength were measured., water-cement ratio, use of silica fume, and the selection of appropriate thickness for the coating rebar is important to protect concrete structures in the region.

KEY WORDS: corrosion reinforced concrete; Persian Gulf; permeability; corrosion current strength; corrosion potentials

Introduction

Infrastructure structures in the Persian Gulf have been increased in the past decades and many of these structures are faced with many problems due to corrosion caused by chloride ion penetration. The main problems include weak implementation, inadequate processing, lack of exposure to environmental conditions as well as unsuitable design for corrosive environmental conditions. Therefore, concrete durability is one of the important requirements for the design and execution of concrete structures is in the southern regions [1]. Damage and degradation of concrete structures affected by corrosive fluids, wet gases, etc. are known as concrete corrosion. Concrete corrosion is a physical - chemical process, while the process of reinforced concrete corrosion is electro-chemical. Many marine wharfs, dock facilities and oil platforms in the Persian Gulf that were built with concrete got exposed to the marine environment and thus they were corroded [2]. The interplay between the concrete and the concrete service environment can lead to the destruction of reinforced concrete structures and in many cases makes structures inappropriate for action based on its design purposes. The interplay is often chemical and environmental [3]. For concrete in marine environments, it seems to be a direct relationship between low permeability, high strength, and good durability. The marine structures such as port buildings and coastal platforms are built using high quality concrete [4]. In general, porous concrete with different size is made from a few angstroms to several millimeters. This system of pores is more or less filled by the solution, including different amounts of salt. Problems related to the use of reinforced concrete in marine environments are well known. These problems have led to extensive researches on the metal corrosion of concrete structures. The reinforced concrete rebar protects concrete against corrosion by the severe alkaline environment (PH=11.5). Therefore, this process limits decomposition [5]. This process occurs by the carbon concrete that reduces the alkalinity or by the presence of small amounts of chloride ion in concrete around the metal. Chloride penetration depth depends on the capability of moisture permeability and the level of oxygen near the surface of the metal. Corrosion occurs in the absence of any of these factors [6]. Corrosion causes metal to become oxides and hydroxides of iron compounds in various stages [7]. This process increases the volume. Such damages caused by corrosion can be seen in the form of parallel cracks to the direction of rebar. Finally, cracking and fragmentation of the concrete occur and the rate of corrosion increases. Progressive collapse can be defined as a chain reaction of collapse. A building undergoes progressive collapse when a primary structural element fails, resulting in the failure of adjoining structural elements, which in turn causes further structural failure. Hence, discussion of resisting progressive collapse for structures arises. In the present study, several samples of the structural steel model with moment frame are designed for seismic requirements. Then, their vulnerability is evaluated for the progressive collapse and it is improved based on a method of retrofitting against the progressive collapse. Finally, the seismic behavior of this system is re-evaluated and the retrofitting effect of progressive collapse on the seismic behavior of the system is evaluated. In other words, the main purpose of this study is to investigate the effect of the seismic retrofitting strategies on the seismic behavior of moment frame structures. Furthermore, this study aims to investigate the durability of concrete containing silica fume, especially chloride penetration and corrosion of reinforcement. Laboratory samples were examined and maintained in two laboratory environments maintenance in the simulated Persian Gulf. Previous studies showed that the amount of chloride penetration and the corrosion rate of concrete containing silica fume are lower than normal concrete. The results are true in both cases of maintenance conditions. In addition, increasing electrical resistance in concrete containing silica in comparison with normal concrete is the most important factor in reducing the corrosion rate.

2. The mechanism of the onset and progression of corrosion of reinforced concrete

Corrosion of steel reinforcement in concrete alkaline environment in accordance with the theory of Tuutti includes the three stages: 1) The incubation period, in which any corrosion does not occur and the rebar is protected due to the protective oxide layer of Fe2O3 .H2O in concrete alkaline environment. 2) The second stage of corrosion starts by penetration of chloride ions into the concrete and the passing of the threshold (0.4% the weight of cement, 0.07 % the weight of concrete), and the reinforcement goes into the active zone. Then, corrosion occurs by providing moisture and oxygen. Corrosion depends on the speed of diffusion of oxygen and humidity. 3) In the third stage, the mechanical destruction of corrosion occurs due to development of concrete. The process of carbonation and chloride ion penetration into the steel surface causes corrosion and cracking of concrete. This process is shown schematically in Figure 1.

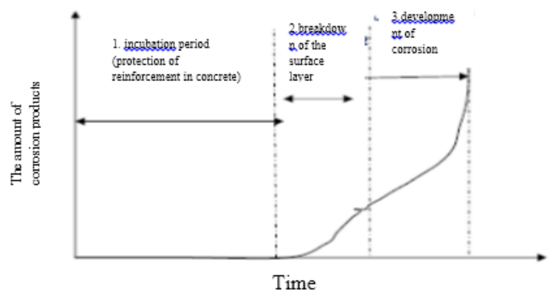

Figure 1: The model proposed by Tuutti, the corrosion of reinforcing steel in concrete [8]

Temperature and high humidity and high concentration of salt in sea water in this region is a big challenge for the coastal structures. For structures located in warm climates, high temperature alone acts as a negative parameter leading to accelerating failure mechanisms in concrete. According to the theory relationship between temperature and the rate of chemical reactions, with an increase of only 10 ° C in ambient temperature, the destruction of concrete structures becomes approximately 2 times [9]. Weather in the eastern part of the Persian Gulf is much warmer than other parts and the temperature changes up to 30 degrees. It has been reported the change of air humidity is between 40 and 95 percent during the day. The minimum and maximum temperature in the region is 3 and 50 ° C and the lowest and the highest humidity is between 5 % and 95 %. There is a big difference between the minimum and maximum of ambient temperature and humidity causing the concrete to be cracked due to thermal and mechanical stresses and penetration of aggressive ions [10]. Mechanical forces arising from the interaction of sea waves with structures can be effectively used to develop some types of collapse in concrete. Figure 2 schematically shows possible collapses in marine concrete with their position. Given the diversity of collapse in this form, it can be concluded that concrete structures in marine environments are exposed to one of the most serious natural environments[11].

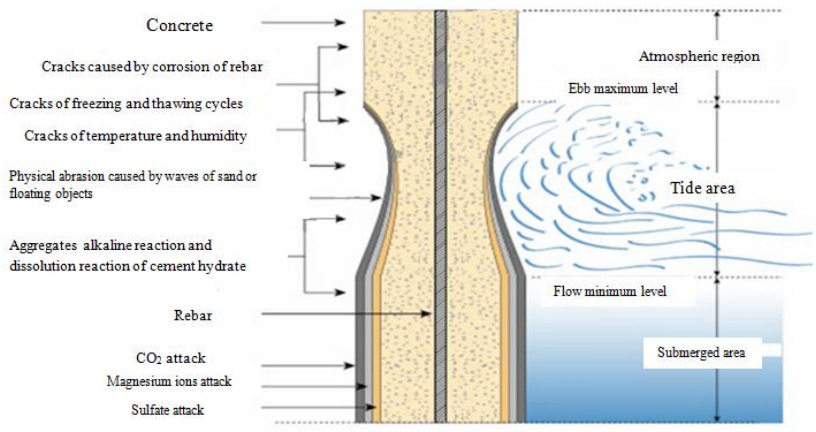

Figure 2: possible collapses and their place in a concrete column in seawater

Climatic conditions of the region

Climatic conditions of the region are hot and dry. Meanwhile, the summers are long and hot and major winds blow from the Arabian Desert. According to the statistics gathered from two weather stations of Dir port and Lengeh port which are the only weather stations and are similar to the aforementioned region in terms of atmospheric characteristics, the average temperature and precipitation in a 25-year period are as follows: The absolute maximum temperature (46 ° C) , absolute minimum temperature (7.5 ° C) , average annual rainfall (220 mm,) maximum daily rainfall (51 mm), maximum wind speed (17 to 18 meters per second).

Saline existing in the Persian Gulf water

The minimum amount of salt in the water is in August and its maximum is in the Strait of Hormuz in February. The average amount of salt in the Persian Gulf water in comparison with the open sea salts in ppm is shown in the following table:

Table 1: The average amount of salt in the Persian Gulf water in comparison with the open sea salts

Salt	open sea water	Persian Gulf water
Calcium salts (Ca)	50 - 480	480
Magnesium salts (Mg)	360 - 14010	1600
Sodium salts (Na)	2190 - 12200	12600
Potassium salts (K)	70 - 550	470
Epsom salts	580 - 2810	3300
Chlorine salts (CL)	3960 - 20000	23400

It is observed that concentration of salt in water of the Persian Gulf is equivalent to or higher than of the open seas. Therefore, the design and construction of onshore and offshore structures must be considered. Consulting engineers of metallurgy and corrosion, Morley and Attlee, estimated by 0.14 mm per year the corrosion in sea water in the Persian Gulf using steel candles in the south of the Persian Gulf.

Laboratory methods and samples

Reinforced concrete specimens dimensionded 20*5*10 centimeters are used to evaluate the corrosion of reinforcement in concrete. The cement used in concrete construction is of type-2 of Hormozgan. Specifications of specimens' incorporation of reinforced concrete with water cement ratio are given in the following table. The largest size of the used aggregates is 19 mm. It should be noted that the thickness of the coating on the armature in specimens of reinforced concrete is 3 cm. The samples are removed from the mold after 24 hours since the time of construction. Then, they are placed in a pool of normal water at a temperature of 25-20 ° C for 72 hours. Next, they are transferred to the anticipated environment.

Table 2: Specifications of Laboratory Samples

Specimen code	Water-cement ratio	Cement content (kilograms per cubic meter)	amount of water (kg per cubic meter)
A1	0.45	400	180
A2	0.5	400	200

In order to assess the environmental conditions, the samples are tested in the following circumstances:
Free zone: the indoor laboratory space of the wet environment (Immersion zone): a pool with Persian Gulf water at a temperature of 30-35 ° C, the water is changed at intervals of a month. Wet and dry zone (tide): The environment is formed by two pools of the Persian Gulf water. Water of pools is pumped to each other. A wet and dry cycle takes places in 24 hours. Each cycle includes 10 hours for wetting and 10 hours for drying. The ambient temperature is 30-35 degrees Celsius. Splash Zone: A pool is used with a wave machine making regular waves. This channel has the Persian Gulf water and samples are exposed to the waves and splash by being placed in the water level. Atmospheric Zone: To simulate this zone, a pump which sprays water with a nozzle in the form of droplets (almost fog like) is used. Samples are placed by some distances from this system to simulate the atmospheric zone as detailed as possible [12]. Potentials of corrosion and the intensity of reinforcement corrosion in different ages on maintained samples are measured in different environments. The corrosion potentials are determined by Half Cell with reference electrode Ag / AgCl at the ages of 28, 60, 90, 120, 150, and 160 days. Potentiostat device is used to measure the intensity of the corrosion. The Wheatstone bridge circuit is used to measure the electrical resistance between at the ages of 90 and 180 days. At the ages of 3 and 6 months, powdered concrete samples are prepared to measure the chloride penetration in depth of 2-3 cm.

The number of samples

In order to execute the above-mentioned tests, some samples are required. Separate samples are used in order to ensure the accuracy of the results and the lack of change incondition in testing different samples. The number of samples in different tests were follows:

Table 3: The number of samples required for testing

test	The number of samples A1 in different environmental conditions					The number of samples A2 in different environmental conditions				
	control	Splash	Immersion	tide	Atmospheric	control	Splash	Immersion	tide	Atmospheric
potentials of corrosion		1	1	1	1		1	1	1	1
Corrosion current		1	1	1	1		1	1	1	1

To assess the results in the chloride ion penetration test, the concrete sample were demolished at the age of 90 and 180 days. Therefore, two numbers of each sample are required to measure the results in two stages. In electrical resistance testing of the control sample, normal treatment conditions are used to compare the results with different environmental conditions. It is tried to place the samples in different environmental conditions similar to the conditions on coast of the Persian Gulf. Also as expected, the permeability of concrete in the test results is effective, the different water-cement ratios for the samples A1 and A2 are considered to create different permeability.

Potentials of corrosion

When a metal is immersed in a solution, potential difference occurs on the surface of liquid and solid due to the non-uniform distribution of the load in the liquid and solid phase. It is impossible to determine fixed potential differences in the level of steel and concrete. Therefore, it is necessary to define the other electrodes to complete the electrical circuit. Potential measured between the electrodes is called pili. In fact, it is the total potential of the two half cells. A constant potential difference can be always obtained by referring to a reference electrode which has a half cell potential. As noted earlier, the electrode used to measure the reinforcement potentials is Ag / AgCl.

Table 4: Range of corrosion potential and corrosion possibility for half-cell of Ag / AgCl

The range of potential	The possibility of corrosion
Lower than -84mv	There is a 90 per cent chance of corrosion activity
Between -84mv and -234mv	The corrosion activity is not definitive, but it is quite possible.
Higher than -234mv	There is a 90 per cent chance of corrosion activity

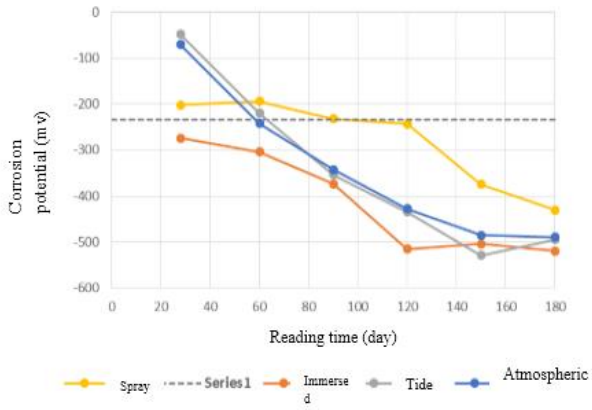

Figure 1: The corrosion potential of samples A1 in different circumstances, at the age of 28, 60, 90, 120, 150 and 180 days

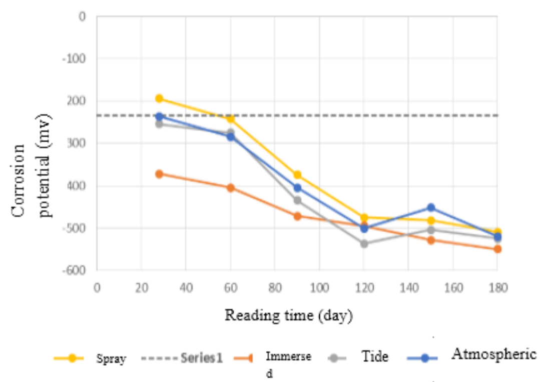

Figure 2: The corrosion potential of samples A2 in different circumstances, at the age of 28, 60, 90, 120, 150 and 180 days

Corrosion current

Potentiostat is used to measure the intensity of corrosion and the results are provided in different environmental conditions at the age of 180 days for samples A1 and A2.

Table 5. The results of corrosion current density for various environmental samples at the age of 180 days

Sample	Immersion	tide	Splash	Atmospheric
A1	0.321	0.393	0.416	0.384
A2	0.586	0.826	1.016	0.674

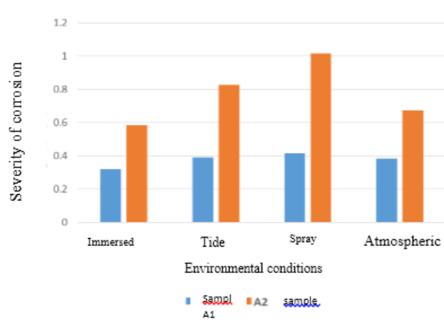

Figure 3: The results of corrosion current density for various environmental samples at the age of 180 days

Table 6: The range of corrosion intensity

Level of corrosion	Corrosion current density ($\mu A/cm^2$)
conditions with low impacts	$I_{corr} < 0.1$
Low to moderate corrosion	$0.1 < I_{corr} < 0.5$
medium to high corrosion	$0.5 < I_{corr} < 1$
high corrosion	$I_{corr} > 1$

Conclusion

In the case of all samples placed in different zones, the electrical resistance decreases over time and will probably leads to an increase in corrosion intensity over time. Comparing the results obtained in this study indicate that the intensity of corrosion is reduced in zones of splash, tidal, atmospheric and immersion. Samples placed in severe corrosive marine environment compared to control environment have a dramatic reduction in electrical resistance. Electric resistance value is reduced and consequently the corrosion intensity increases because of the increase in moisture and chloride penetration into concrete. Samples placed in the splash zone has the lowest electrical resistance in comparison with zones of immersion, tides and atmospheric. The reason is the increase in penetration of chloride ions into the concrete pores that further reduces electrical resistance of concrete and increases intensity corrosion of reinforcement. The splash zone is the most difficult situation in terms of corrosion because increasing amount of moisture and the amount of free chlorine in the concrete and the existence of sufficient oxygen increase corrosion intensity. In immersion zone, although the corrosion potential of reinforcement is very high, the intensity corrosion is minimal due to lack of oxygen. Permeability can be minimized by increasing amount of micro silica and decreasing the water - cementitious materials ratio. The size of coating greater than 5 cm is recommended for concrete structures exposed to tides.

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