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Reinforcement Corrosion of a Post-Tensioned Steam Cured Concrete Jetty in the Persian Gulf Region

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ABSTRACT: Concrete deterioration and corrosion of reinforcement in severe condition of the Persian Gulf cause enormous damages to marine structures. In this study, a set of destructive and nondestructive tests was performed on different reinforced concrete elements of a jetty located in the marine environment of the south of Iran. The purpose of the project was evaluation the level of damage in the jetty structure which were constructed by post-tensioned beams made with steam cured high performance concrete (HPC). The results revealed negligible corrosion level in the most elements of the jetty especially those with sufficient concrete cover. However, despite the use of high-strength concrete in the construction of the jetty structure, inadequate cover thickness for some reinforced concrete elements intensified corrosion rate and caused early age corrosion problems. Therefore, based on the test results, a rehabilitation strategy was proposed to repair the jetty.

1 INTRODUCTION

Reinforced concrete (RC) is by far the most frequently used construction material worldwide.
Despite the fact that concrete is a reliable structural material with a good durability performance, exposure to severe environments makes it vulnerable (Bertolini et. al.). Many of structures, even new constructed RC structures have suffered from reinforcement corrosion and a significant cost for the repair and other associated issues is annually imposed (Bertolini et. al.). Corrosion of reinforcing bars induced by chloride ion ingress is a major cause of damage in marine and road environments (Bertolini et al. & Mehta). The corrosion damage in these concrete infrastructures is often observed by rust-staining of the surface and cracking and spalling of the concrete cover due to the formation of expansive corrosion products. Chloride can destroy the protective film on steel bars leading to corrosion of reinforcement and decreasing the reinforcing steel cross-section that, in turn, results in the loss of serviceability often much earlier than the designed service life of the structure (Mehta).
Most of the research on corrosion has been based on laboratory tests while these tests are not completely representative of the in situ behavior of reinforced concrete structures. There is a need for further investigation of reinforced concrete structures exposed to real aggressive environments to improve the findings about corrosion mechanisms as well as the methods of construction of resistant structures. Studying of concrete structures under natural exposure conditions is the aim of this work.
The outcome of the work is expected to help professionals in obtaining more conservative predictions of durability performance of concrete structures in harsh environments and minimizing the deterioration of future constructions.

2 JETTY STRUCTURE

The jetty is located in the northern coast of the Persian Gulf, north of Strait of Hormoz, near the port of Bandar-Abbas. The structural layout is shown in Figure 1 and consists of two main parts which are the Unloading Pier and Channel Bridge.

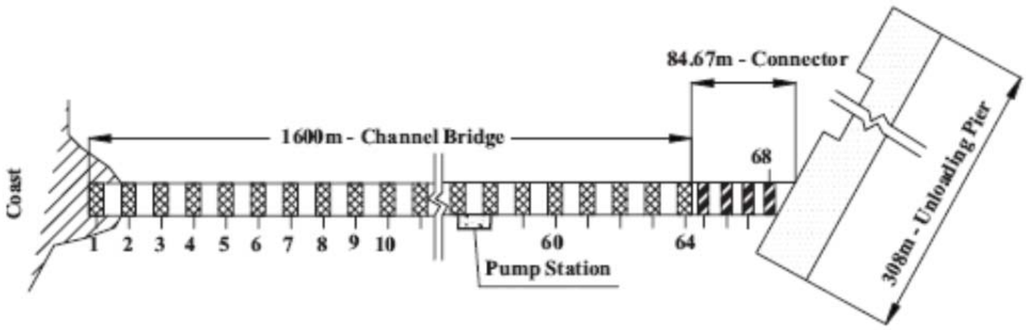


Figure 1. General layout of the RC jetty structure

The jetty was constructed at the beginning of the 1990s as a loading dock for minerals such as iron ore. The unloading pier is made from cast-in-place RC cross girders along with steel concrete composite deck, and the channel bridge consists of a 64 span bridge with the length of 1600 m which connects the unloading pier and the coast. Every span is composed of three post-tensioned box girders and two steel cross girder-pile systems.
The concrete mixture used met the criteria specified for durable concrete in the Persian Gulf region. Cement content was about 440 kg/m^3 and water to cement ratio was 0.34. The only deviation from the code was the use of ASTM Type I Portland cement which according to ACI 318-05 and ACI 350-01 is not recommended under moderate seawater sulfate exposure. The concrete elements were designed for nominal compressive strength of 40 MPa.

3 EXPOSURE CONDITION

This structure is located in a region classified as hot and wet according to the climatic classifications of Fookes et al.
The average day time temperature varies from 18°C in January to 34°C in July, while day time temperature reaches as high as 50°C in summertime. The average daily relative humidity ranges from 60% in October to 70% in February with the maximum (since 1957) recorded relative humidity of 98%.

4 RESULTS OF INSPECTION

4.1 Visual Inspection

Thorough visual inspection would be helpful in investigation of deterioration, and in some cases, it can characterize the causes. This could provide researchers with primary information about structure conditions and extension of deterioration. Thus, appropriate visual inspection helps in selection of the type, number, and suitable location of tests. An in-depth inspection, carried out to assess the condition of the jetty, revealed several deterioration degrees as follow:

1-Upper and inner surfaces of channel bridge beams looked undamaged. It seemed that sufficient concrete cover thickness of reinforcement and use of high quality concrete were two main reasons for soundness of the structure in these parts.

2-Most of the repair works were unsuccessful and cracks were visible in surrounding areas. It seems that the most important cause of this phenomenon is incompatibility between repair and base concrete. Moreover, a structural weakness is possible near the supporting points where the shear forces are maximal (Figure 2-a).

3-Extensive reinforcement corrosion was visible in the bottom of channel bridge (Figure 2-b). Low concrete cover thickness, high humidity under the jetty and possible splashing of seawater could be the main causes.

4-Patch repair works caused the formation of incipient anode in vicinity areas which is the sign of electrochemical incompatibility (Figure 2-c).

5-High rate of corrosion was visible in fenders and some other areas near the seawater (Figure 2-d).

4.2 Compressive Strength and Water Absorption

Concrete cores were drilled from different parts of the jetty for determination of compressive strength and water absorption according to ASTM C 42 and BS 1881-122, respectively. Figure 3 illustrates compressive strength of more than 50 obtained cores. The average value is more than 50 MPa with a standard deviation of 8.1 MPa which implies suitable mechanical properties of the concrete. High value of compressive strength was expected based on the mentioned mix design; results of tests on concrete cores confirm appropriate casting and curing procedure. This is very good compared with other structures that have been built in Iran. It is mentioned that the minimum water-to-cement ratio recommended by ACI 357 (ACI 1997) in a marine environment is 0.4 for the splash zone, and the minimum recommended compressive strength is 35 MPa. Thus, the mechanical quality of the used concrete was in accordance with common standard codes.

Figure 4 also shows 30 minutes water absorption test on 21 concrete cores. The average is about 1.2% which indicates high quality of the concrete. There is no significant standard that provides a criterion for the water absorption or void content value because these parameters depend on various conditions such as aggregate type. However, the Iranian national code of practice for concrete durability in the Persian Gulf and the Sea of Oman (BHRC 2005) has limited 30-min water absorption to 2% for severe conditions. Therefore, almost all of the samples were acceptable according to this standard. Based on the results of compressive strength and water absorption, the quality of concrete used in construction of the jetty seems to be above the acceptable values in references. Further tests were performed to confirm this idea. The results of electrical resistivity test on concrete cores are presented in the next part.

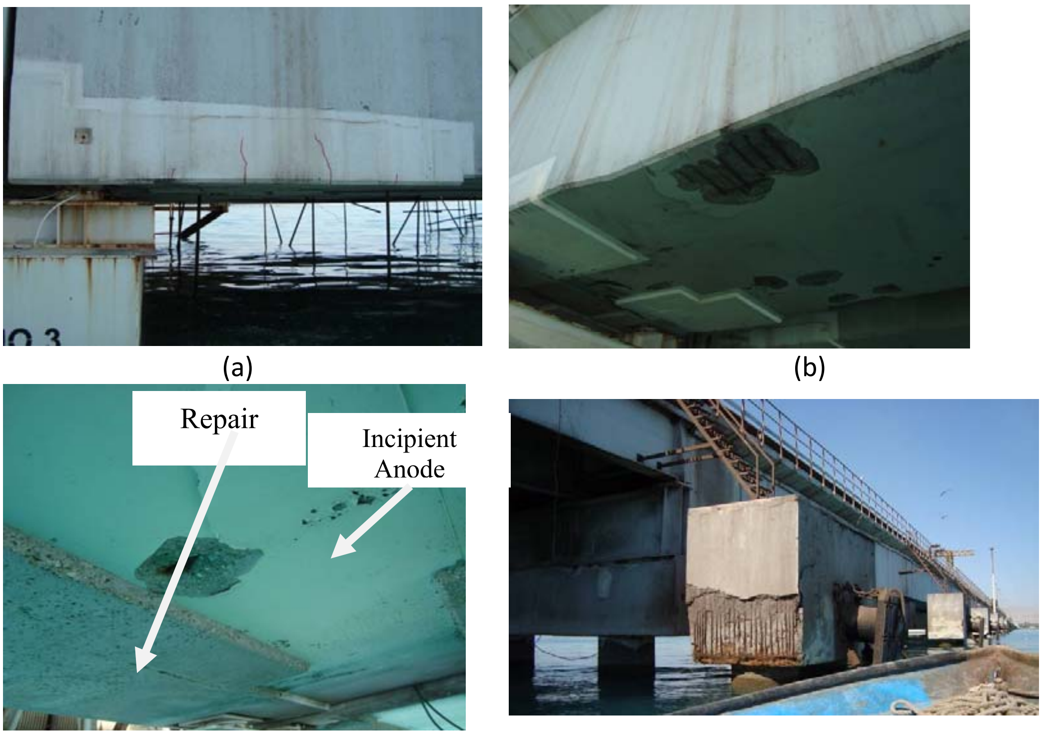


Figure 2- a) Crack occurrence in supporting points b)reinforcement corrosion under Channel bridge c) formation of incipient anode d) corrosion in fenders

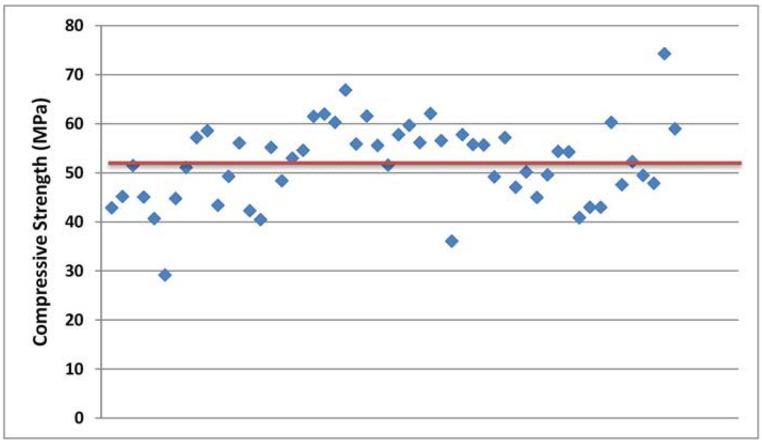


Figure 3. Compressive Strength in different parts of the jetty

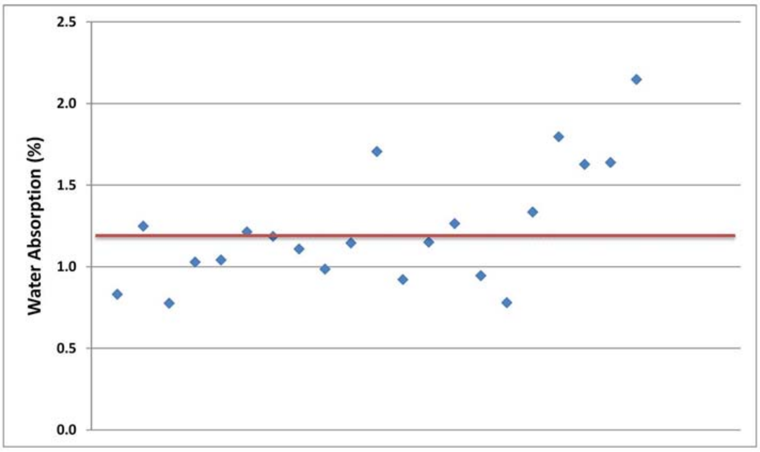


Figure 4. 30 minutes water absorption in different parts of the jetty

4.3 Electrical Resistivity

Electrical resistivity is a fundamental property of a material, which characterizes that material almost as completely as its density (Whittington et. al.). A test was carried out on saturated surface dry concrete cores based on the impedance spectroscopy method in the same moisture and temperature conditions (Shekarchi et. al.) and results are presented in Figure 5.
The average electrical resistivity of the concrete is about 15.7 KΩ-cm. The ACI 222R-01 code provides some ranges in which the concrete resistivity and corrosion rate may be related. Based on this reference, the rate of corrosion is low which means high quality of the used concrete.

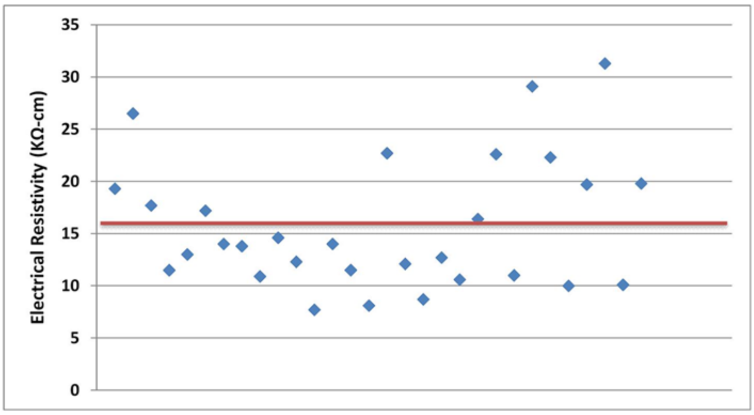


Figure 5. Electrical resistivity of concrete cores in different parts of the jetty

4.4 Cover Thickness

Concrete cover is the main protective layer against weather and other aggressive effects, and the time to corrosion initiation for conventional carbon steel is most sensitive to its cover depth (Zhang et. al.). The concrete cover for steel reinforcement was measured, and the results indicate that the cover thickness varies in different parts of the jetty. Figure 6-a, 6-b, and 6-c illustrate the cover thickness in bottom of a beam near the coast, an area on channel bridge and uploading pier, respectively. As can be seen in the figures, the cover thickness in (a) and (c) is less than (b). However, in most areas of (a) and (b), the cover thickness is more than 50 mm. For splash and atmospheric zone exposure conditions, a minimum concrete cover of 90 mm should be used American Concrete Institute (ACI) 357R-84. It is noteworthy that there were some areas in bottom of channel bridge with a cover thickness of less than 20 mm (Figure 2-c). Though, access to those areas was not possible and visual inspection adopted for investigation.

4.5 Half-Cell Potential Method

The half-cell potential method (ASTM C876) is a common electrochemical method for evaluating the corrosion activity in the reinforcement of concrete. It is a nondestructive means for locating areas of corrosion for monitoring and condition assessment and in determining the effectiveness of repair work (Shekarchi et. al.). Half-cell potentials were measured versus a silver/silver chloride electrode (SCE). The probability of corrosion was interpreted by ASTM C876-91 (Table 1).

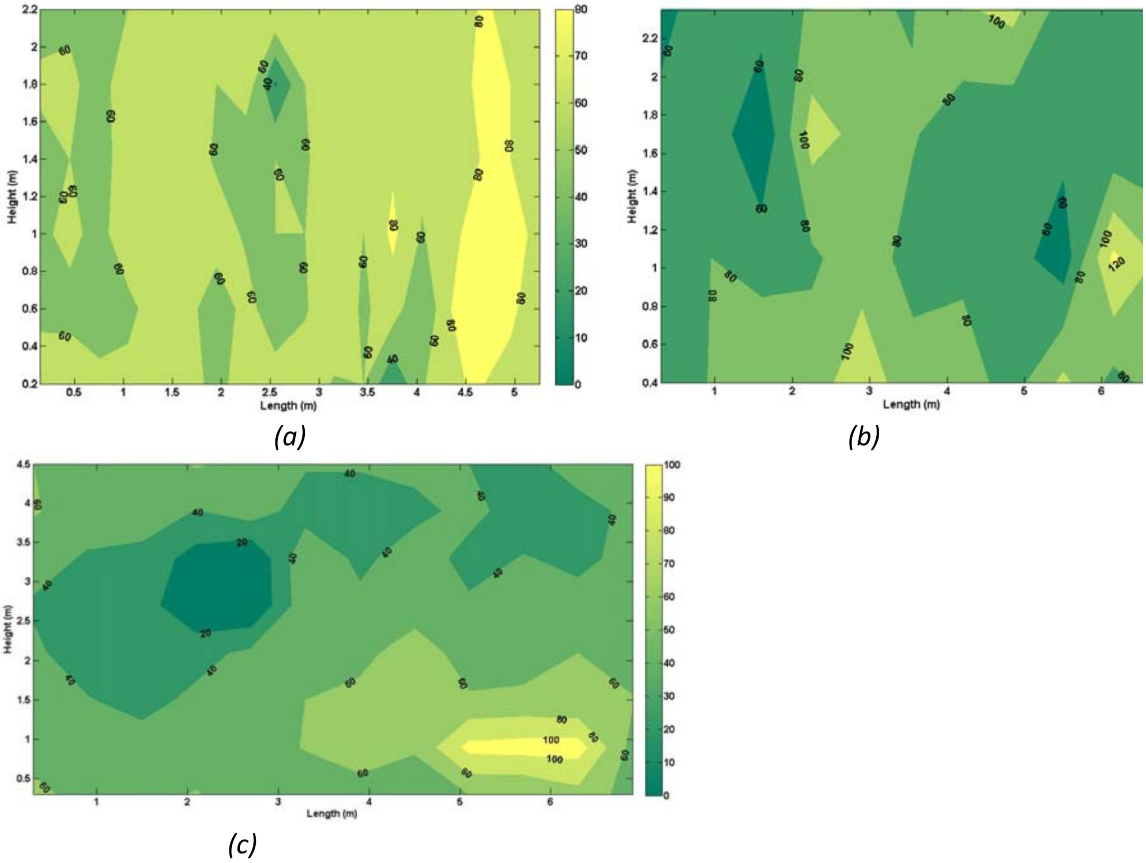


Fig. 6. Cover thickness (mm) in a) bottom of a beam near the coast, b) an area on channel bridge, c) an area on uploading pier

Table. 1. Evaluation of Corrosion Activity versus Silver/Silver Chloride Electrode

Potential versus	Interpretation
EAg > -83 mV	More than 90% probability that no corrosion is occurring
-233 mV < EAg < -83 mV	Corrosion activity is uncertain
EAg < -233 mV	More than 90% probability that corrosion is occurring

The half-cell potential contours in different parts of the jetty are presented in Figure 7. Repaired areas is shown in Fig 7-a. Based on the ASTM C876, the probability of corrosion is more than 90% in most areas of this surface. The repaired areas have become a cathode which accelerates the corrosion in neighborhoods. In addition, repaired areas themselves have critical potentials as well. Thus, the patch repair work seems to be unsuccessful in this case. The reasons could be insufficient cover thickness, humidity of this part of the jetty, possibility of splashing of the seawater, and hot climate of the region. Wet surface of this part was visible in visual inspection. In spite of high rate of corrosion in (a), the process of deterioration in upper and inner sides seem to be substantially lower or negligible. Only some local corrosion occurrences were detected in channel bridge (Figure 7-b). The test was performed on several other areas of this element of the jetty. High quality of concrete and adequate cover thickness could be the reasons for lower corrosion. However, the corrosion rate was higher in uploading pier (Figure 7-c). Lower cover thickness and position of this part in the sea could be some possible causes.

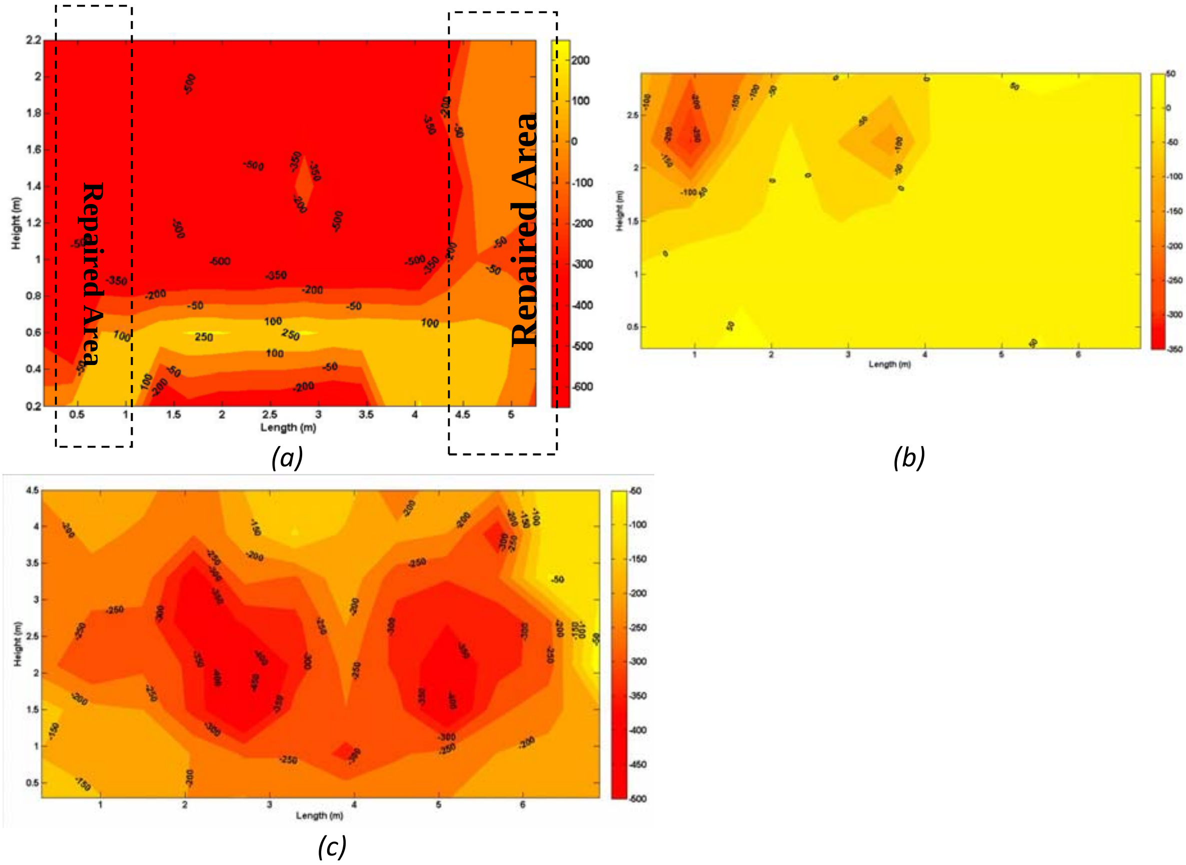
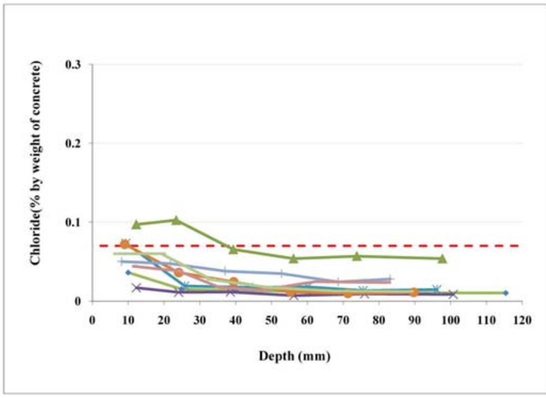


Figure 7. Half-cell potential contours (mV) in a) bottom of a beam near the coast, b) an area on channel bridge, c) an area on uploading pier

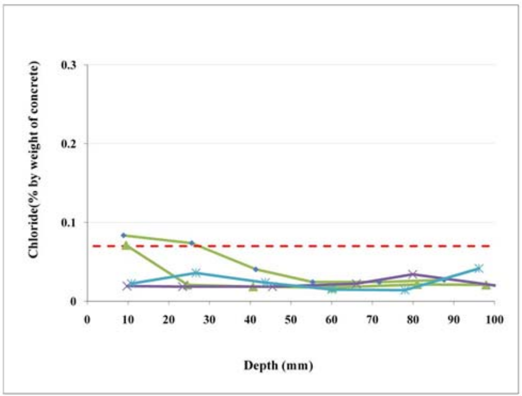
4.6 *Chloride Penetration*

This test was performed on powder samples obtained from the selected structural members at different depths of the concrete. The chloride content measurement was carried out in the laboratory according to ASTM C114 and results are presented in Figure 8.According to report of Angst et al. the chloride threshold value for corrosion initiation of reinforcement considered between 0.015 to 0.3 percent by concrete weight. BS 8110, recommends 0.4% chloride content by weight of cement as the threshold value. The chloride content on top of channel bridge and inner surface of beams was low (Figure 8-a and 8-b). Minor signs of corrosion were visible on these areas. However, chloride penetration in uploading pier was higher comparing to mentioned parts (Figure 8-c). Chloride ions have penetrated to some concrete surfaces near the seawater (Figure 8-d).

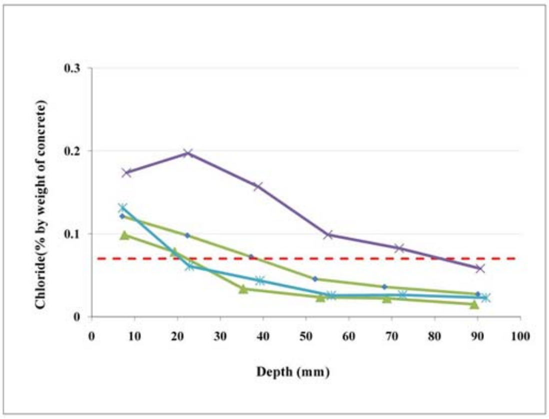
Effectiveness of repair works was examined in one location near the coast by measuring chloride penetration as well (Figure 8-e). It seems that the applied repair was not useful and chloride ions penetrate into the concrete. Meanwhile, carbonation test was performed on several points of the jetty using the traditional RILEM CPC-18 method and a negligible depth of carbonation was observed. It is known that high humidity and salt crystallization on the surface of concrete elements in marine structures usually prevent CO_2 diffusion as a protection against carbonation (Castro & AlKhaiat).



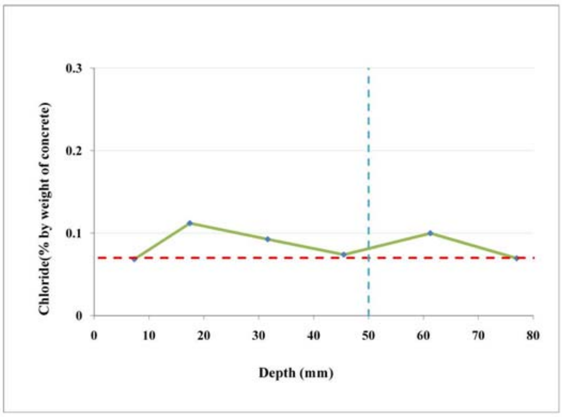
(a)-D



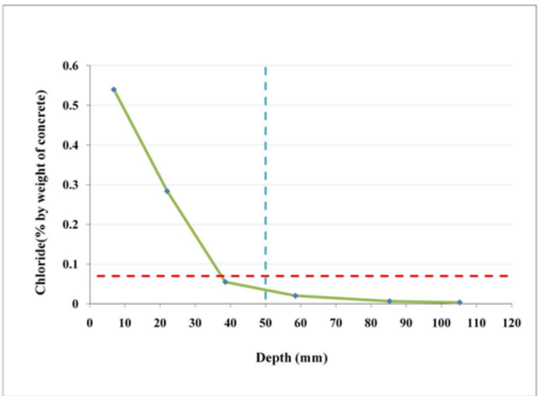
b-T



(c)-J



(d)-B



(e)-B

Figure 8. Chloride profiles a) on top of channel bridge b) inner parts of Channel bridge c) in uploading pier d) in a surface near the seawater e) in a repaired point

5 REHABILITATION STRATEGIES

Considering great economic and strategic importance of the jetty, it should be repaired without substantial disruption in operation. The repair methodology adopted consisted of the total removal of the superficial layer of deteriorated and chloride-contaminated concrete in bottom of channel bridge to a depth beyond the reinforcing bars, and replacement by a new high-quality concrete. Several bars were corroded and they must be replaced with new ones. Repair concrete must be compatible with substrate and durable with a sufficient cover thickness. Concrete mix properties like low w/c ratio or admixture addition could substantially affect the durability of concrete in the marine environment. Using concrete with lower w/c ratio including pozzolanic admixtures especially silica fume, improves the permeability and resistance to chloride diffusion into concrete structures in marine environment. It must be noticed that dimensional compatibility between substrate and repair concrete must be considered. Dimensional and electrochemical incompatibility between repair and substrate concrete causes further corrosion in repaired areas. Eventually, use of proper type of available coatings on the new casted concrete repair could increase the life time of the structures (Shekarchi et al.).

6 CONCLUSION

This paper mainly discusses the results of the assessment of a reinforced concrete jetty in a marine environment. This jetty structure is an example of insufficient planning and weak construction from the technical and construction point of view. The results of tests performed on concrete cores (compressive strength, water absorption, and electrical resistivity) showed high quality of concrete. While the structural design is well within guidelines of the accepted and conventional RC structures, the lack of understanding of the durable aspects for concrete structures in the Persian Gulf region, e.g., inadequate concrete cover thickness and concrete transport properties, has led to severe corrosion behavior in some parts of the jetty. The inspections carried out showed that the principal mechanism responsible for the extensive deterioration of the structure studied is chloride-induced reinforcement corrosion. This mechanism led to extensive delamination and spalling of the concrete cover. Dimensional and electrochemical incompatibility between repair and substrate concrete led to further corrosion in repaired areas. The removal of deteriorated concrete and rebars and replacement with new, durable ones could be a suitable alternative for the rehabilitation of the construction.

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