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Evaluation and rehabilitation of Shuwaikh Port in Kuwait

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ABSTRACT

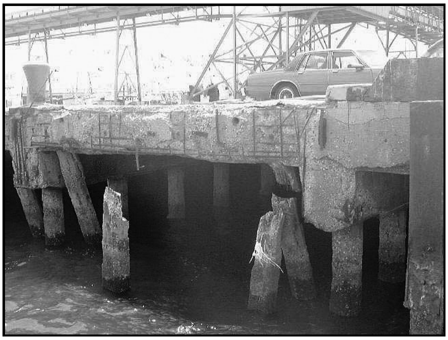
Shuwaikh Port in Kuwait was put into operation in 1960 but has had no systematic maintenance regime in place and has neither planned or undergone a major repair since the commissioning of the port. Accordingly, the process of degradation and deterioration of the whole of the infrastructure of the Port is becoming obvious and apparent. The preliminary visual inspection of the Port indicated widespread cracking, spalling and corrosion of reinforced concrete elements. Subsequently, a number of destructive and non-destructive tests were undertaken for the rehabilitation work to be carried out. This paper reports the investigation undertaken and presents the results of the above testing and the rehabilitative measures recommended to the Kuwait Port Authorities (KPA).

Keywords: Visual inspection; destructive and non-destructive testing; port rehabilitation; marine exposure

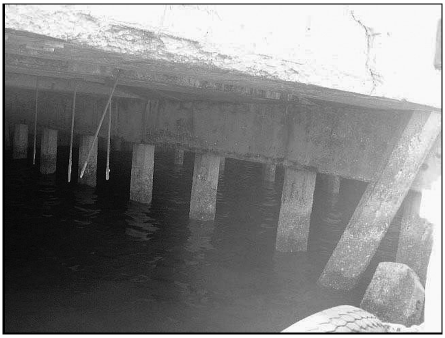
INTRODUCTION

Durability of concrete structures in a marine environment is a challenging issue because of the aggressiveness of sea water on concrete and reinforcement. Shuwaikh Port is one of three major ports in Kuwait and came into operation in 1960. In addition to the marine exposure conditions in the Port, the prevalent weather in Kuwait is characterized by extreme hot and dry conditions. There has been no systematic maintenance regime in place and neither has a planned or major repair been undertaken since the commissioning of the port. Accordingly, the process of degradation and deterioration of the whole of the infrastructure of the port is becoming obvious and apparent. This paper presents the evaluation of Shuwaikh Port along with recommendations on its rehabilitation.

The wharfs structural system at Shuwaikh is comprised of wharfs supported on piles, wharfs supported on seawalls, and piers supported on piles providing berthing for smaller vessels. Figure 1 shows an overview of the existing conditions at the Port. The principal structural elements included coping or edge beams, seawalls, slab deck - pre-stressed deck units of a slab top and slab soffit, cross beams (across the shortest axis of structures), and longitudinal beams (running parallel to the longest axis of structures) made of typical beams and rail support beams. Support piles include vertical and diagonal, square and octagonal piles, fender piles, and wharf furniture (bollards and fenders).



(1) Impact damage, total loss of structural section of piles & exposed reinforcement



(2) Cracking / spalling of cross beams with corrosion staining. Note reinforcement hanging from the soffit

(3) Coping beam & cross beam end cracked & spalled

(4) Extensive damage to the coping beam and cross beams

Fig. 1. Overview of existing conditions in Shuwaikh Port

Tide and structure levels: The mean high water surface (MHWS) is +4.1 m, the mean low water surface is +0.8 m, the tidal range is +3.3 m, the cross beam - soffit level is +3.8 m, the longitudinal beams - soffit level is +4.7 m, the slab - soffit level is +5.0 m, and the slab top surface is +5.2 m.

Marine structures may be considered in terms of exposure conditions, whereby the following industry accepted zones are classified:

Atmospheric zone	Above the splash zone
Splash zone	0.5 to 1.5 m above the highest tide level
Tidal zone	Between lowest and highest tide level
Submerged zone	Below lowest tide level (permanently submerged)
Seabed zone	Part of structure buried under the seabed

Typically, the area of a marine structure that is at the highest risk of corrosion is in the splash zone, which is about 0.5 to 1.5 m above the MHWS level. For a relatively sheltered port structure such as Shuwaikh Port, the splash zone was considered to be around 1 m above the highest tide level. This exposure zone is subject to constant wetting and drying from waves (wind driven and from bow waves of berthing/passing vessels) and has both chlorides and oxygen in abundance to initiate and maintain corrosion.

The tidal heights and levels of the structure given above identify that the entire structure from the slab soffit and below lies within the splash zone and hence is subject to the highest risk and rates of corrosion. Although the slab top is just outside the nominal 1 m above the highest tide level, horizontal top surfaces allow ponding of seawater and wind deposited salt to remain on their surface. The inter-tidal and atmospheric zones are considered to be medium risk corrosion zones, while the submerged and seabed zones represent the lowest corrosion risks.

CORROSION INITIATION DUE TO CHLORIDE INGRESS

The dominant mechanism of degradation of marine structures in the Shuwaikh Port is chloride induced corrosion which is based on the chloride transport into concrete by diffusion and by the initiation of reinforcement corrosion when a critical chloride content is exceeded at the steel surface. Diffusion modelling of chloride ingress into concrete was proposed in the 1970s and is now well developed (Collepardi, et al. 1972, Bamforth & Price 1993, Maage et al. 1996). After the critical "threshold" chloride content has reached the steel and has broken down its normal passivation at which point the steel starts to dissolve. Dissolved iron ions react to form corrosion products at some point in time causing expansive stresses and cracking of concrete cover. Eventually, the loss of a steel cross section may become critical with respect to the structural capacity (Vrouwenvelder & Schiessl 1999). The two-stage concept of initiation and propagation of corrosion was developed by Tuutti (1982).

In summary, the chloride induced failure of concrete occurs when $C > C_{crit}$, with C the chloride content at the reinforcement surface and C_{crit} the critical (threshold) content. The critical chloride content is a complex function of concrete properties (pH, water, oxygen, presence of voids) at the steel/concrete interface. It is realised that there is no single value, but rather a gradual increase in the probability of corrosion with increasing chloride content (Vaassie 1984, Polder & Rooij 2005). For concrete structures a value of 0.5% chloride ion by mass of cement is considered to be the mean critical value for Portland cement concrete (Polder & Rooij 2005).

DETAILED VISUAL SURVEY OF WHARFS FOR STRUCTURAL EVALUATION

To develop a proper maintenance and rehabilitation program for the wharfs, a thorough and comprehensive visual survey of their current condition, in terms of extent and severity of damage, was undertaken. This survey was done in two distinct stages. The first stage was an initial walk around all the wharfs of the Shuwaikh Port. The second stage included a comprehensive and detailed survey, wharf by wharf and structural element by element, using launches and small boats to be as close to the structural elements as possible. For practically, most visual inspection sessions were videoed, photographed, and documented on drawings.

The first impression from the visual survey was that the whole infrastructure was in disrepair. Most structural elements exhibited extensive and wide cracking, delamination, visible corrosion in advanced stages of propagation and even broken reinforcement. A general view, shown in Fig. 1 is indicative of the extent of disrepair at the Shuwaikh Port.

Results of Visual Inspection: As mentioned earlier, a detailed and thorough visual inspection was done at the seven wharfs (from no. 2 through 8) in Shuwaikh Port. The structural elements such as piles, pile caps, beams and slabs were all inspected. Further, the damage level of a particular element at a given location was determined by observing the extent of distresses and their manifestations including (ACI 1998); crack propagation, spalling, delamination, rusting, staining, weathering and severed reinforcement bars and tendons (ACI 1998).

A damage grade was assigned after observing the extent of the seven characteristics (as given above) at a particular location. To be more definitive, the photographs (and videos) taken on a given location on a particular element (beam etc.) were re-examined, when in doubt. The damage levels were observed and consequently graded at hundreds of locations on various structural elements on all seven wharfs and tabulated. This information was also used in deciding the repair methodologies and materials to be adopted. Typical photographs showing type and extent of structural degradation were included, similar to those shown in Fig. 1, to get a graphic view of the extent of damage.

Conclusions drawn from visual inspection: As expected, the extent of damage in various structural elements varied from wharf to wharf. The structural damage on wharf no. 2 appeared to be more extensive and widespread. In contrast, wharfs 5, 6, 7 and 8 were the least damaged. The structural damage on wharfs 3 and 4 was of intermediary level. Comparatively speaking, pile caps and main beams were more damaged. In addition to obtaining an overall estimate of the magnitude of the problem, the data obtained from visual inspection was of great help in the determination of repair options.

FIELD AND LABORATORY INVESTIGATION OF STRUCTURAL ELEMENTS ON WHARFS

The two most important objectives of this investigation were to determine:

1 - Safety and serviceability of the port, and

2 - The maintenance and rehabilitation techniques to maximize the life of the structure at a minimal but necessary cost.

The two main objectives could be realized by undertaking structural and material characterization. The results of the visual survey had already provided a global, but only indicative, view of the extent of the damage. In order to be more definitive some additional parameters were required. Accordingly, the following material characteristics were deemed necessary:

1 - Strength of the in-place concrete by extracting cores;

2 - Chloride content in concrete sampled from differing elements at varying stages of degradation;

3 - Sulphate content of the concrete samples;

4 - Depth and extent of carbonation in structural elements;

5 - Extent of corrosion and loss of section of the reinforcement;

6 - Loss of concrete cover to the rebar in differing locations of the structures; and

7 - pH of sea water and its salt concentration.

The above material and environmental parameters were used to estimate the structural capacities of the various elements in addition to estimating the residual life. The information and data thus generated lead to the repair materials and strategies to be adopted.

Estimation of Compressive Strength of the In-place Concrete

Concrete cores of approximately 70 and 100 mm in diameter and 100 and 120 mm in length were extracted from piles, pile caps, beams and slabs from all wharf locations undergoing differing degrees of degradation. The cores were cut and tested according to ASTM C42-99M (2003) by means of a rotary cutting tool with diamond bits. Cores give an estimate of both strength and visual inspection of the interior region of a member. In addition, other physical properties of concrete, such as its density, water absorption and cover to reinforcement were also examined in the cores. Cores were also used as samples for chemical analysis (determination of chloride and sulphate contents) following strength testing.

Cylinder strength of the cores extracted varies between 29 to 59 MPa. These strength results clearly establish that the in-place concrete is still sufficiently strong. So in spite of the fact that there is large scale deep cracking, spalling, corrosion and even rupture of rebars, the substrate concrete is still sufficiently strong and managing to support the wharf structures on the whole. This, of course, was encouraging. The density of wharf concrete, on average, is about 2300 kg/m^3 which is indicative of its good quality. Accordingly, the density of the substrate concrete also corroborates the compressive strength results.

To get an overall estimate of the insitu strength of the various structural elements on individual wharfs, average values of strength were obtained for each wharf and are included in Table 1. Again, these average strength values establish that on each wharf, concrete in the pile, pile caps, beams and slabs is of adequate strength.

Table 1. Average values of estimated standard cylinder insitu strength for wharfs 2 through 8

Location	Compressive Strength (MPa)			
	Pile	Pile cap	Beam	Slab
Wharf 2	36	41	55	59
Wharf 3	36	35	50	37
Wharf 4	44	35	30	42
Wharf 5	42	36	40	44
Wharf 6	39	33	39	33
Wharf 7	34	33	36	33
Wharf 8	40	41	41	29
Average (of all Wharfs)	38.8	36.3	41.4	39.8

In summary, the present compressive strength of the concrete in the wharfs of Shuwaikh Port is still adequate as given by cores extracted from differing structural elements. This strength, however, is not indicative of the structural integrity of the wharfs because it represents the concrete between the cracks and spalls.

Chloride Content Determination

Chloride penetration into concrete and its access to reinforcement in concrete causes pitting corrosion and depassivates steel. There are very stringent limits of chloride concentration in concrete to avoid localized and general corrosion and hence cracking, spalling and widespread disintegration of concrete structures, exposed to a marine environment. For example, ACI Building Code (318-05) puts a maximum limit of 0.15% of water soluble chloride for structures exposed to chloride in service. Accordingly, determination of chloride concentration is a very important test to assess the present state and future performance of a marine structure. Slices were obtained from the extracted cores to determine their chloride content. In this investigation chloride concentration was measured using the Rapid Chloride Tester-RCT (2003). However, several chloride determinations were also performed using chemical analysis techniques recommended by British and ASTM standards (1988). Comparable results were obtained by both methods establishing that results given by the Rapid Chloride Tester were reliable.

The chloride content (percent by weight of cement), of samples extracted from piles, pile caps, beams and slabs from wharfs 2-8 were determined. The chloride concentration was determined at 5 depths; from 0-20, 20-40, 40-60, 60-80 and 80-100 mm, respectively.

The chloride levels varied from a minimum of 0.10 to an extremely high value of 10.23% by weight of cement. In particular, surface chloride concentration on the pile-caps were exceptionally high with a minimum value of 6.42% on wharf 6. Chloride concentration on beams was even higher than those of the pile caps with a minimum value of 7.69%. As can be seen, the chloride concentrations in the depth 60-100 mm are somewhat low (AS-3600 1994, ACI 318M 2002). On the average, the chloride concentration found are an order of magnitude higher than those permitted in marine structures.

The average value of chloride contents were determined and are included in Fig. 3. As can be seen, the chloride ion concentration on the surface of all the elements are prohibitively high. It is very important to note that the chloride levels on the reinforcement location (at the cover depth) in piles, pile caps, beams and slabs are approximately 0.2, 0.7, 0.8 and 0.2%, respectively, by weight of cement (see Fig. 2). These chloride concentrations are certainly high in marine conditions and for marine structures, but are not excessively high.

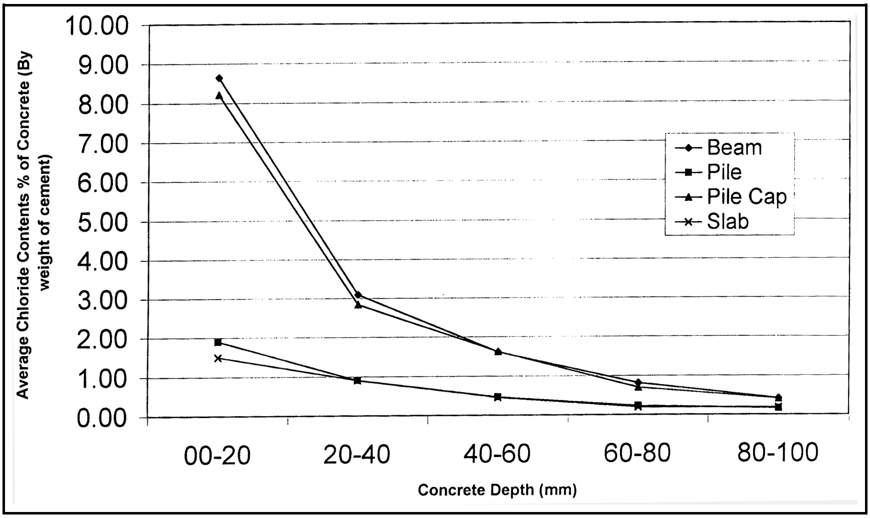


Fig. 2. Average chloride contents for all the wharfs in piles, pile caps, beams and slabs (% by weight of cement) in wharfs 2 through 8

In summary, excessively high surface deposition of chloride on beams and pile caps has been found. In addition, surface chlorides on the pile and slabs were also high. Nonetheless, the chloride concentration at the reinforcement level is still moderate and of the order of 0.4% of cement. The industry norm, however, for the Middle East for "standard" reinforced concrete is generally taken to be 0.3% by weight of cement (Haque & Al-Khaiat 2000).

For concrete containing pre-stressed steel, the higher stresses in the steel render the steel more vulnerable to stress corrosion cracking. However, most failures are due to macro-cell corrosion reducing the load carrying capacity of the steel.

Threshold values for concrete containing pre-stressed steel cited in ACI 22R-96 are quoted as being 0.08% by weight of cement (based on the commonly used acid soluble testing method - ASTM C1151 (1990). This is significant for this structure as the piles and the deck units are pre-stressed elements.

Sulphate Content Determination

Sulphate from soils and seawater can cause expansion and hence cracking and premature degradation of concrete. There are prescribed limits beyond which sulphate concentration in concrete should not increase (AS-3600 1994, ACI 318M 2002). Like chloride, sulphate content is determined on slices extracted from cores, according to BS 1881, Part 124 (1988).

The sulphate content, percent by mass of cement, was determined on various structural elements. Sulphate content as determined, varied from a minimum of 0.70 to a maximum of 8.85% on the Shuwaikh port structures. Most concrete structure codes allow a limiting value of 5% (AS-3600 1994). Sulphate contents of that order found on these wharfs can damage concrete by a crystal growth mechanism. Accordingly, it was concluded that the accumulation of high sulphate contents in wharf structures, have also contributed to the degradation of facilities at Shuwaikh Port.

Carbonation Depth of Concrete

As a result of penetration of CO2, the pH of concrete drops. The depth of penetration of CO2 is called carbonation depth. The carbonation depth depends on the quality, strength and age of concrete and the exposure conditions (Al-Khaiat et al 2002). If the concrete in which steel is embedded becomes carbonated, then the passivity of protective oxide film on the steel surface can no longer be maintained. The depassivation of this film results in the initiation of rusting, provided that optimum moisture and oxygen are available.

The depth of carbonation on (100 mm diameter) cores of 100 mm in diameter extracted from different structural elements was determined by treating freshly split concrete with a phenolphthalein indicator.

In most structural elements there was almost no penetration of the carbonation front. This was expected as in marine conditions, the concrete is almost saturated and hence the carbonation front cannot advance. Concrete carbonates the most between 60 to 70% relative humidity. It is noted that on an isolated spot on a beam in wharf 3, the depth of carbonation recorded was 12 mm. It is concluded that carbonation has not contributed to the degradation of concrete in Shuwaikh Port.

Permeability Measurement

Concrete with a low permeability is the best defence against penetration of damaging species into concrete and hence, a trouble-free, life-long performance. In this investigation, water permeability through the concrete surface was monitored using the AUTOCLAM system (1996). In this commercially available system, the protective quality of concrete based on CLAM indices is as shown in the Table 2. The values of the CLAM permeability index was determined on pile, pile caps and slabs on all the 7 wharfs. According to the above criteria, certainly the permeability indexes obtained on pile caps and beams suggest that the concrete is of high permeability. In piles and slabs the concrete permeability can be rated as good. The results suggest that in those structural elements where chloride concentration was high, the permeability index was also high, suggesting concrete is more permeable, which is the case. Values taken ranged from an index value of 6.2 indicating a good protective quality to 13.6 ($m^3 \times 10^{-7}/min)^{0.5}$, indicating a very poor protective quality. This is indicative of the variable concrete quality.

Table 2. Indicative quality of concrete using clam water permeability index

Clam Water Permeability Index (m3? 10-7/min.-0.5)	Protective Quality of Concrete
< 3.7	Very Good
> = 3.7, < 9.4	Good
> = 9.4, < 13.8	Poor
> = 13.8	Very Poor

Determination of Concrete Cover

The concrete cover thickness was obtained with the use of a magnetic covermeter in accordance with BS and ASTM standards. Electromagnetic cover devices can be used for determining the position and direction of steel reinforcement and depth of cover to the steel. This information is essential for both the estimation of the capacity of a structural member and its future performance.

The concrete cover to reinforcement on piles, pile caps, beam and slabs was measured using a micro covermeter on wharfs 2 through 8. Measured cover varied between 57 to 99 mm, which is typical for marine structures. The cover to reinforcement in all cases was found quite adequate. The average value of the cover measured for piles, pile caps, beams and slabs was 75, 90, 90 and 65 mm, respectively.

Summary of the Test Results

As can be seen from the results reported in this section, a rigorous and planned testing on all the structural elements of wharfs 2 through 8 at Shuwaikh Port has been undertaken. In all, about 50 concrete cores of 70 and 100 mm in diameter were extracted from piles, pile caps, beams and slabs. The results of the testing are satisfactory, and as conclusive as could be. A summary of the results is:

1 - The concrete, in-between cracks and spalls, in most structural elements is still sound and of adequate compressive strength in the range of 29 to 59 MPa.

2 - The chlorides and sulfates concentrations on the skin of all the structural elements are dangerously high and most cracking, spalling and steel corrosion, which is widespread, are due to the expansive pressure caused due to chloride and salt crystallization and its growth.

3 - Although high, chloride and sulfate levels as seen in the profiles are not dangerously high beyond 50 mm of the surface concrete. In particular, the present chloride ion concentration at steel level in all structural elements is about 0.4%, by weight of cement, and the presence of advanced stage of corrosion can be witnessed.

4 - Cover to reinforcement, where there is no cracking and spalling, is adequate and still of good quality concrete. An average value of cover to reinforcement in piles, pile caps, beams land slabs is 75, 90, 90 and 65 mm, respectively.

Overall, the age of the wharfs 2 through 8, in tandem with thorough visual inspection and test data (particularly chloride and sulfate ingress and salt crystallization) suggest that many parts of the structure are now at a very high risk of corrosion related damage becoming much more widespread. Remedial works carried out early will help arrest the corrosion before this manifests on a larger scale.

STRUCTURAL ANALYSIS OF WHARFS

The structural assessment for all wharfs was performed, based on the available drawings and information. Commercial software, STAAD III Ver. 22.3, was used in the analysis to check the adequacy of the various elements in the structures.

The structure system for all the wharfs is the same, consisting of pile foundations on soil, pile caps, main beams and the slabs (decking). The piles and slabs are precast prestressed members.

For each structural element, the compressive strength of concrete is based on the results of concrete testing given earlier. Also, the concrete cover to reinforcement used in the analysis is based on the results obtained in the field. Broken piles were noted and two runs were carried out where the broken piles were considered in the first run and deleted in the second run.

A 3D structural analysis was carried out for each wharf. The analysis was performed for the slabs and pile caps using the finite element method. The end of pile caps supports were considered to determine the reactions for the floor system. These reactions were then considered as loads on piles to determine the existing forces acting on the piles.

The following is a very brief summary of results:

1 - All existing beam dimensions and reinforcement were found adequate. Likewise slab thickness and reinforcement were adequate.

2 - The maximum working load for piles in wharfs 2 to 5 is 1120 kN, 870 kN for wharf 6 and 1250 kN for piles in wharf 8. The load capacity for piles is 1650 kN for wharfs 2 to 5 and 2040 kN for wharfs 6 and 7 and 1840 kN for wharfs 8, with a factor of safety of 2.5. This means that all the existing piles are adequate according to the loads supplied by the Kuwait Port Authority.

3 - In wharfs 6 and 8 where some piles were broken, the analysis resulted in high negative moments in the pile caps and high working loads for other adjacent piles.

In summary, wharfs in the present state were found structurally adequate except portions of wharfs 6 and 8 where some piles were broken and structural members were near failure.

RECOMMENDATIONS FOR REHABILITATION AND REMEDIATION

The maintenance of marine structures, of course, is a continuous on-going process. One option for repair is the replacement of the deteriorated concrete with new material. Pneumatically applied polymer based, with and without fibers, cement concrete and mortar remain the main materials for above water concrete repairs (Buslor 1992).

On concrete wharfs and piers, where the highest deterioration has occurred on the overhead (soffit) surfaces of the superstructure, overlays are impractical. This leaves shortcrete as the only realistic possibility. Hundreds of structures around the world have been repaired by replacement of deteriorated concrete with pneumatically applied high-cement-content high strength mortar. Theoretically shortcrete should provide durable repairs, and in some cases, these repairs did have a long life. Unfortunately, the overall performance of shortcrete repairs on marine structures has been mediocre, at best (Buslor 1992).

Many remedial alternatives were considered and budgeted and their cost-benefit ratios were evaluated. Finally, the following were recommended to the KPA, to enhance the life of Port for another 15 years.

1 - Only well-developed, well-propagated and visible degradation (where spalling, corrosion, loss of section and wide cracks were apparent) was to be repaired.

2 - Many, if not all, of the repairs, included in Table 3, will have to be undertaken to restore the full serviceability of the Shuwaikh Port.

Table 3. Repair strategies recommended to the Kuwait Port Authority

Description	Remedial Recommendation
Support piles	Replace affected lengths of piles where entire section/part of the section has been lost. Piles requiring local patch repairs and protection from further corrosion. Install Life Jackets.
Beams	Patch repair and install mesh anode.
Slab soffits	Patch repair and install mesh anode.
Seawalls (not berths) in tidal area	Install galvanic mesh anode.
Seawalls (berths) above tidal area	Patch repair and install anodes.
Coping beam sides/tops	Patch repair and install galvanic anode.
Slab tops	Patch repair and galvanic anode. Apply a coating of slurry.
Patch repairs	Use render mortars (proprietary products).
Protective coatings	Many proprietary products are available (polymers and paints).
Steel plates	Strengthening of elements, e.g. strengthening of crane beams if required to handle larger cranes.

Remediation Works

As can be seen in Table 3, the main and major remediation of the port infrastructure is to be achieved by the addition of a galvanic cathodic protection system. This consists of employing prefabricated Expanded Zinc Mesh Anodes and Zinc Mesh Anode Jackets. The prefabricated zinc mesh anodes are mechanically fixed and compressed to the concrete surface by proprietary means.

As an example, there were 17 concrete piles in the port which had badly spalled and corroded and had shown very high levels of chloride concentration. These piles needed to be protected, in addition to the patch repair. This was to be achieved by installation of a Zinc Mesh Life Jackets (LJ) system. The installation of the LJs was to be carried out as per the recommendation and instructions of the manufacturers (suppliers) and their technical advisors. Again, most of pile caps which are running across the wharf width were to be cathodically protected with an overlay zinc-mesh system. The cathodic installation system was to be designed to achieve a service life of at least 15 years.

SUMMARY AND CONCLUSIONS

A comprehensive evaluation of the Shuwaikh Port is presented in this study. The investigation shows an extensive degradation of the main structural elements of wharfs.

It is important to consider the harsh environment of Kuwait when designing such a structure. The structural type of the port and the materials used should be selected properly to obtain highly durable port infrastructure.

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تقييم وتأهيل ميناء الشويخ في الكويت

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خلاصة

بدء التشغيل بميناء الشويخ عام 1960 إلا أنه خلال تلك الفترة لم تكن هناك صيانة منظمة ولم يتعرض إلى إصلاحات مدروسة. ونتج عن ذلك تدهور واضح في شامل منشآت الميناء. والفحوصات النظرية الأولية أوضحت بشكل كبير حدوث الشروخ وتساقط الخرسانة وصدأ حديد التسليح وكان ذلك منتشر في جميع أنحاء الميناء. وقد استخدمت الفحوصات المتلفة وغير المتلفة لفحص العناصر الإنشائية لإعادة تأهيل الميناء. وهذا البحث يقدم نتائج الفحوصات والتقييم لمنشآت الميناء إضافة إلى تقديم التوصيات لتأهيل الميناء.