Construction and maintenance of concrete piles in corrosive and destructive marine environments, based on study of the Persian Gulf marine installations

Nasser Arafati[1], AbdolHossein Fazli[2], Seyed Mehdi Mousavi[2], Fouzieh Rouzmehr[3]

Assistant Professor, Department of Civil Engineering, Tafresh University, Tafresh, Iran, Postal Code 3951879611 arafati@aut.ac.ir

Research Assistant, Department of Civil Engineering, Tafresh University, Tafresh, Iran, Postal Code 3951879611 hfazli@live.com

Research Assistant, Department Engineering, Tafresh University, Tafresh, Iran, Postal Code 3951879611 s.m.moosavi@tafreshu.ac.ir

Research Assistant, Department of Civil Engineering, Guilan University

Gilan, Iran, Postal Code 1841 fouziehrouzmehr@yahoo.com

Abstract

Marine environments include ions and corrosive gases and are the place of marine living things, which are destructive for construction materials. Hydrostatic pressures and high temperature changes, which are current in most of the coastal areas and marine structures, are able to accelerate decay of construction materials. Marine structures and port installations existing in ports are considered as important infrastructural installations that due to their concrete or metal nature are exposed to decay and destruction arising from being in marine environments. Concrete piles, which are executed in sea beds or in coasts, are affected by corrosive factors and the factors decreasing stability. Therefore methods and materials and special inspection system should be used to confront these factors. Undoubtedly Persian Gulf is one of the most corrosive and risky environments of the world for execution of concrete structures and concrete piles.

This research tries to investigate the optimum methods for execution and maintenance and optimization of concrete piles and also concrete technology of these piles in Persian Gulf in details. In order to access this aim the geotechnical experiences of the piles and foundations executed in Persian Gulf and Omman Sea were used and finally some proposals for execution of such structures in destructive environments without any problem were offered.

1. Introduction

Generally, ease of use of driven piles in marine environments caused their more extensive application as compared with drilled shafts. Using driven piles in marine environments was started since Neolithic times. The first residents of the globe used to utilize such piles for construction of their houses on water in flood plains and different types of bridges on rivers.

For execution of driven piles different methods have been used since that time up to now [1]. In the past very simple and time-consuming methods and equipment were used but nowadays precise and very quick and modern methods and equipment are employed. Modern equipment can be employed by contractors to ensure safe, quick and adequate installation of driven piles. Global Positioning Systems (GPS) aid in survey and accurate layout of pile locations. New hammers are capable of energy adjustments and monitoring to provide the required hammer performance while protecting the piles from damage. Instruments can be used during testing and installation to confirm the design and pile load capabilities. In addition to the problems related to common piles, piles problems in marine environments include the problems arising from the corrosive water environment. Some of these problems are Liquefaction of saturated sands during pile installation, settlement around piles, heave, buoyancy and hydrostatic pressure [1], [2].

One of the most important problems we encounter in marine environments is splash zone effect and a more important problem is the severe corrosive effect of some of the marine environments on piles.

At present one of the most corrosive marine environments of the world is Persian Gulf in the south of Iran. Due to abundant amount of salts and ions existing in this environment, concrete piles are under severe decay and destruction.

Very corrosive climatic conditions, insufficient knowledge of the executive personnel, weakness in construction stages, application of improper and low quality materials, etc. are some of the factors of different types of destruction of concrete structures in Persian Gulf marine environments.

Current regulations of concrete production and piles execution, which have been considered for execution in the other points of the world, are not suitable for such an environment and create a lot of problems. There are a lot of samples of problems occurred in such structures in 1990s.

1.1 General descriptions of exposure conditions

Surely Persian Gulf is one of the most corrosive and aggressive environments for concrete structures particularly concrete piles; drilled piles and driven piles. As it is shown in "Table.1"

In comparison with other seas in the world, Persian Gulf has more chloride ions than others. This content surely increases durability risk in these environments, also jeopardize reinforcements to corrosion. Temperature difference between night and day is about 25-35 centigrade,"Fig.1" and humidity difference is high too,"Fig.2". [3, 4]

Thus executing method and concrete technology of piles and other concrete structures should be unique in this Gulf.

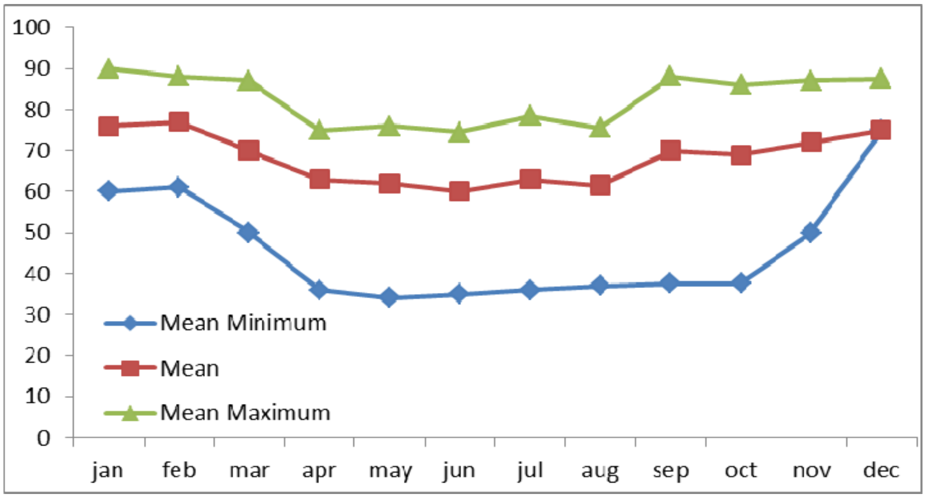

Figure.1.Montly relative Humidity averages

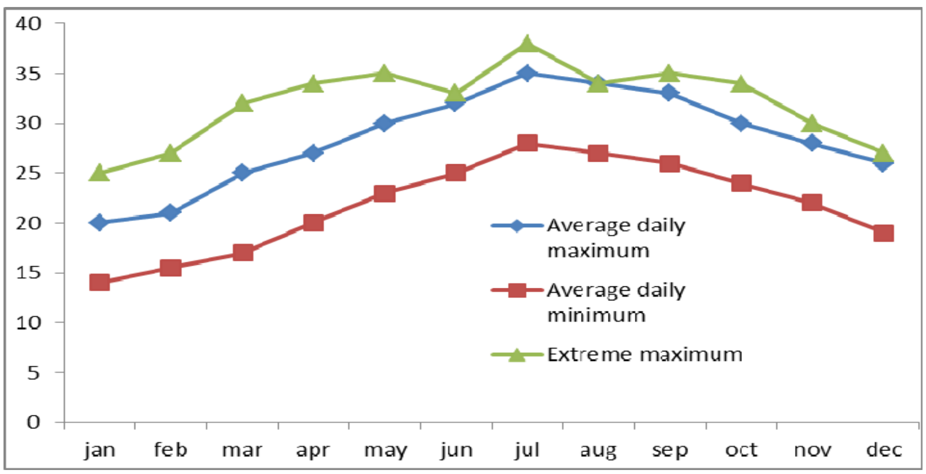

Figure.2.Montly Temperature

ions	Baltic sea	Atlantic sea	North sea	Mediterranean sea	Persian Gulf
K++	180	430	400	420	450
Ca++	190	410	430	470	430
Mg++	600	1500	1330	1780	1460
So4-	1250	2540	2780	3060	2720
Na+	4980	9950	11050	11560	12400
Cl-	8960	17830	19890	21380	21450
Salt Content	16200	32600	35900	38700	38900

Table 1: ions content in world seas.

1.2 Pile selection:

Due to high corrosion risk for steel piles, pre stressed or pre tensioned concrete piles are recommended for this environments [5]. Quality control, efficient increased strength and durability, sufficient curing, manufacturing precision are advantages of pre stressed and pre tensioned driven piles in comparison with drilled piles in these environments. The most important issue during all kinds of works is management of execution and safety. They'll be more important when we're talking about underground or underwater operations.

2 First mandatory steps

Quality control during fabrication is an important issue; the piling must be checked for material defects upon arriving at the jobsite. The piling and associated connectors must also be protected from damage from the time they are offloaded onto the jobsite until they have been installed in the ground [6].

During the driving or excavation of piles these items should be checked [7]:

- the line of excavation or driving
- the final depth of the excavation or driving
- the location of any underground services or other hazards

Positional accuracy is required during all phases of the project. At all locations and during all phases of the construction, three-dimensional (3-D) boundary locations and tolerances must be verified [6].

Whichever method is used, the operator must be given the exact depth and width of cut. The excavation line and any underground services or hazards should be marked.

2.1 Installing method

The most common method of installing piles is dynamic impact from a variety of hammer types. Vibratory hammers and impact hammers are usually used in pile execution under water. The majority of underwater piles have been installed using impact-driven methods, although vibratory-driven methods are gaining in popularity for offshore operations. The principal reason that offshore vibratory hammers are not as popular as impact hammers is due to the larger offshore pile weights, which require greater vibration energy [6]. Selection of the proper hammer not only involves matching the required load capacity, soil conditions, and piling properties to the hammer, but also includes a requirement to minimize excessive stresses during driving, to prevent damage to the piling by overdriving.

3. Inspection of piles

Inspection of waterfront facilities specially underwater piles involves the application of special skills, equipment and techniques to examine underwater structures. Priorities for inspections of piles under water are tidal zone and mud zone. Under most conditions, the recommended frequency for underwater inspection is six years. In historically polluted waters like Persian Gulf structures should be inspected every three years. The frequency of re-inspection depends on the type and material of construction, water conditions, and the condition assessment. The most important of these is the construction material.

We have four types of investigations for underwater constructions [8], [9]:
I. Routine Underwater Inspection: To obtain data on general condition, to confirm and update drawings, and to make estimated cost of repairs for planning purposes.
II. Underwater Engineering or Underwater Design Surveys: To obtain data necessary for design, specifications, and detailed cost estimates.
III. Underwater Acceptance Inspection: To confirm that repair or construction has been completed according to plans and specifications.
IV. Underwater Research: To obtain information for research projects such as the rate of deterioration.
Drilled foundations (piles and caissons), require a higher degree of inspection and monitoring because of the high potential for development of unforeseen problems.
For driven-pile foundations these inspections should be done [6]:

- Quality of pile materials and connectors
- Damage during driving
- Pile heave
- Ground vibration and movement
- Subterranean water
- Workmanship and materials during installation
- Load testing

Because of significant damage that has been done during the 90^{s} due to lack of knowledge of pile execution in Persian Gulf, all of these types of inspections (specially IV for a great number of deteriorated piles in the zone) should be done in Persian Gulf water front facilities to prevent more hazardous problems.

4 Backgrounds

Reinforcement's corrosion is usually most considerable issue in deteriorated marine concrete structures, induced chloride ion affects on durability of concrete structures in severe exposures. Chloride ions which penetrate through cracks or voids or diffusion through matrix cause to onset of pitting corrosion when their concentration at the steel surface exceeds a critical threshold value. This threshold depends on several factors, such as pH of concrete, steel potential and presence of micro voids in the cement paste [10, 11, 12 and 13].

One procedure to prevent or delay the corrosion is covering piles with epoxy resins [14], since piles are more risky in tidal/splash zones, epoxy resins can protect piles from connection between seawater and concrete layer.

Another way is providing cathodic prevention by means of sacrificial anodes [10], [15]. Often cathodic protection cost is higher than strengthed concrete which has optimum strength and durability, so high cost of this method is one of the disadvantages of this method. Contractors prefer to increase material quality and quality control instead of using cathodic protection.

Chloride ions influx through cracks that exist on concrete cover of piles. After considerable time, corrosion starts when ions connected to reinforcements, thus preventing penetration of chloride ions is important step in piles and marine concrete structures. In addition chloride penetration increases voids [22] thus deterioration risk arises consequently.

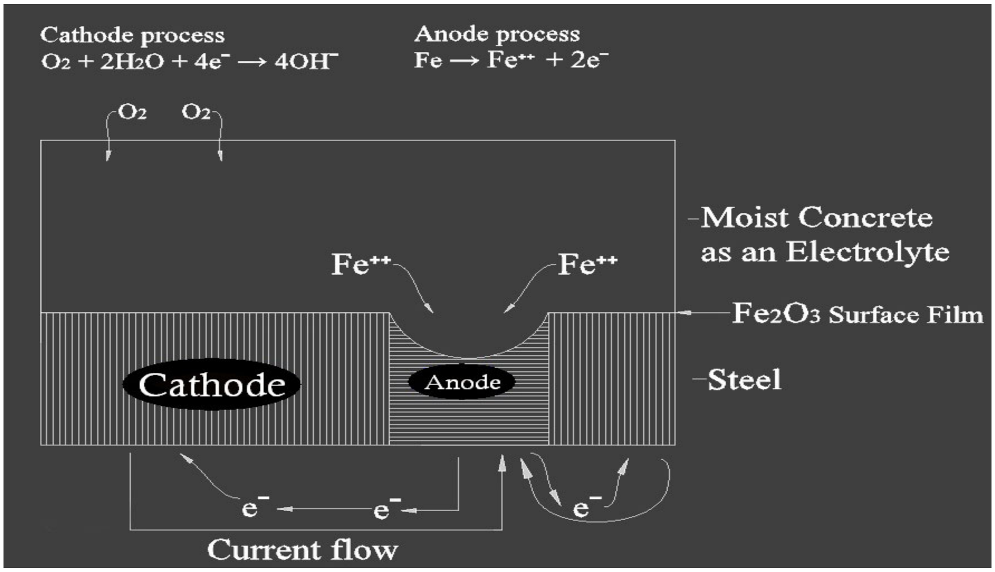

Figure 3

Fig.3, "*illustrate the electrochemical process of steel corrosion in moist and permeable concrete .The galvanic cell constitutes an anode process and a cathode process. The anode process cannot occur until the protective or the passive iron oxide film is either removed in an acidic environment (e.g., carbonation of concrete) or made permeable by the action of CL- ions. The cathodic process cannot occur until a sufficient supply of oxygen and water is available at steel surface. The electrical resistivity of concrete is also in the presence of moisture and salt*", Mehta et al [15]

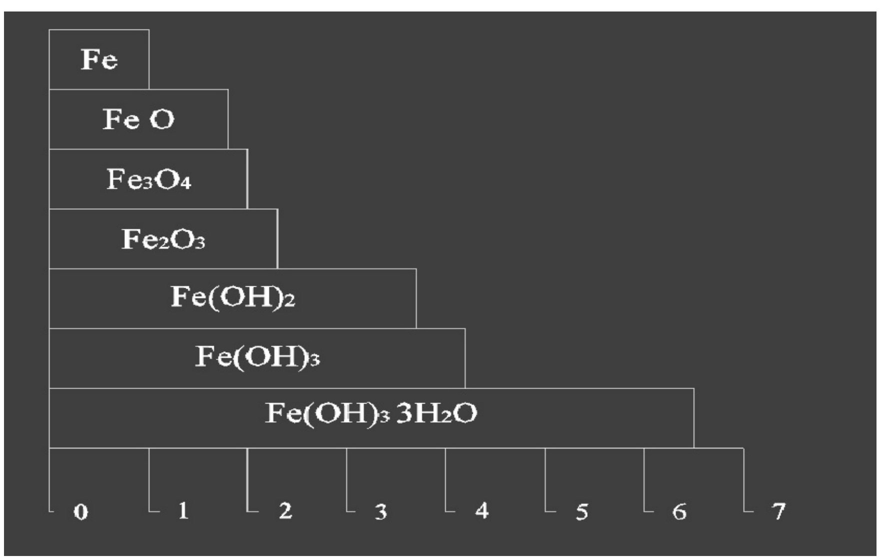

Figure.4

Fig.4, "*shows that depending on the oxidation state, the corrosion of metallic iron can result in up to six times increase in the solid volume*", Mehta et al [15]

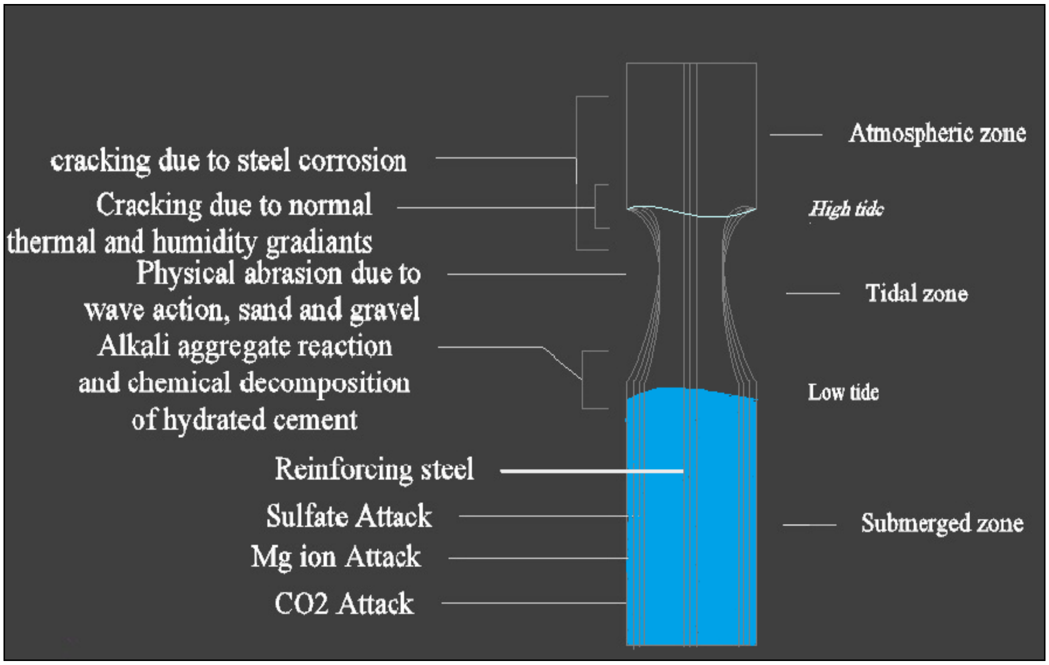

Figure. 5

Figure.5: Diagrammatic representation of reinforced concrete cylinder exposed to seawater (From Mehta, P.P., *Performance of Concrete in Marine Environment*, ACI SP-65, pp.1_20, 1980) [27].
"*The type and severity of attack on a concrete sea structure depends on the conditions of exposure. The sections of structure that remain fully submerged are rarely subjected to frost action or corrosion of embedded steel. Concrete at this exposure condition will be susceptible to chemical attacks. The selection above the high-tide mark will be vulnerable to both frost action and corrosion of the embedded steel. The most severe deterioration is likely to take place in the tidal zone because here the structure is exposed to all kinds of physical and chemical attacks" Mehta et al* [15].

5 Materials

5.1 Cement and replacements

There was a view that cements type (V) is suitable and also more durable than type(I) ,(II).but experiences in concrete structures and concrete piles in Persian Gulf shows that structures which are made of cement type (V) has more deterioration than structures which are made of cement type (I),(II) [16].Also M. Naderi showed that concrete prisms which contains cement type(I) has more chloride penetration resistance than concrete prism which contains cement type (II) [14]. Using type (V) reduces durability of concrete considerably. Moreover references [17],[18]

prove this claim that replacing fly ash by 15% cement content increase strength and durability of concrete structures and moreover it is proven that it can increase initiation time to corrosion,15% fly ash and w/b=0.4 can delay corrosion initiation until 60 years [19].
As reference [20] shows, replacing calcium chloride by 2-4% cement content , that is used as setting accelerator was recognized as a corrosion cause in pre stressed tendons. So it is prohibited to replacing calcium chloride as cement replacement or hardening accelerator.
Although voids and entrained air can increase permeability and consequently decrease durability but according Haynes, H. H, air entrain by 2-6 % doesn't increase permeability[19], and it is recommended for concrete piles in Persian Gulf. It can reduce cracks which are caused by temperature gradients and also it can increase workability and slump (consequently it will be easier to compacting and casting successfully).

According to A.Shayan experiments, replacing Glass powder as a pozzolanic material reduces chloride ion penetration [23] utilization this material in concrete is highly recommended in casting marine piles and marine structures.
Coastal concrete structures in Netherland that made by cements with blast furnace slag showed no corrosion after 30 years. Although it is possible that corrosion initiated after 20 years but no corrosion detected in 88% of 64 structures [25]

5.2 Aggregate

Aggregates contain 60-80 % concrete volume and are considered as inactive material in concrete structures but it is not allowed to neglect effect of aggregate types on marine structures especially which are in severe exposure and aggressive environments. Aggregates are cause of abnormal dimensional stability and durability depletion.
A.Shayan experiments, which is a comparison between non-reactive, slowly reactive, highly reactive behavior in seawater proves this claim that it is not allowed to utilize highly reactive aggregates and it is suggested not to use slowly reactive aggregates in high temperature [24].Expansion of highly reactive is recognized as deterioration cause in marine concrete structures in south of Iran and Persian Gulf shores.
Limestone and non-reactive dolomite aggregates or sufficiently high level of other forms of carbonate calcium have desirable corrosion properties R.E.Melchers *et al* [14]. Limestone favorable corrosion properties can observe in Escambia Bay Bridge, piles in tidal zones didn't have any significant corrosion after 30 years [24].
It is highly recommended to rinse aggregate before use. It lets concrete to reduce alkalinity and consequently reduce expansion of pile thus it will be easier to reduce surface cracks.

5.3 Water Quality

Due to delicacy of piles, it is not allowed to use sea water for producing concrete, although concrete prism which is made by sea water can reach up to 90% of compression strength of ordinary water (edible), but it isn't recommended to use seawater or any salty water.

6 Execution and design notice

Reducing w/b is the most important element to have durable, strengthen, corrosion protected, and any other desirable issues. As Woosuk [19] showed, lowering w/b about 0.05 is more effective than 13mm (1/2 inch) increment of cover thickness. It means that the piles with 51mm(2inch)clear cover and w/b=0.35 act better than the piles with 76mm(3inch) cover and w/b=0.4 .In marine splash/tidal exposures, Woosuk et al [19], showed that service life of piles with w/b=0.3 concrete mixture and 51mm (2 inch) clear cover is more than 100 years.

Thermal gradient during steam curing, transporting by inexperienced performers, using improper driving hammer, inadequate driving, should be controlled by executors to prevent premature cracks.

Protecting pile by covering epoxy resin that is a method to prevent of corrosion needs highly experienced workers to isolate piles completely from moisture.

7 Conclusion

As it was observed, with due attention to the very especial conditions of the Persian Gulf with a view to both very corrosive environment and abundant number of coastal constructions it was tried to present the best method for piles selection and execution with use of the most recent researches and executed samples. In brief the results were as follows:

-Use of pre-stressed or pre-tensioned driven piles
-Covering piles with epoxy resins for splash zones
-Using cement type (1) or (2)
-Replacing fly ash by 15% cement or even higher
-Not using calcium chloride
-Aid entrain by 2-6%
-Using glass powder as a pozzolanic material
-Using non-reactive aggregates
-Using limestone and non-reactive dolomite aggregates of carbonate calcium
-Rinsing aggregate before use
-Not using marine water for concrete production
-Reducing w/b
-Employment of experienced and trained personnel

We also recommend these steps for a accurated and scheduled program for management of execution and inspection of piles:

-Checking the line of driving of pile
-Locating of any underground services or other hazards
-Using dynamic hammer for installation of piles
-Performing a scheduled investigation program for piles (including new piles for problems like hammering defects, pile heave and old piles for reconstruction).

Using the above-mentioned method causes much increase in life of the piles executed in the Persian Gulf environment, in such a way that with execution of these methods corrosion is started much later. In such conditions we can make sure of the confident performance of the executed structure during its lifetime.

In addition to increment of piles execution quality, another preference of execution of the above-mentioned methods is economizing of construction and execution activities of such resistant to corrosion piles, which is another positive factor for encouragement of contractors for execution of these methods.

8 REFERENCES

[1]Foundatioun Engineering: In the wet design and counstruction of civil works projects, "U.S Army corps of engineers", No: 1110-2-565

[2] R.J Jardine,"*Review of technical issues relating to foundations and geotechnics for offshore installations in the UKCS*", First published 2009, Imperial College London

[3] Concrete in Hot countries,*"Office of the deputy for technical affairs bureau of technical affairs and standards*", No: 184

[4] A.R. A1-Rabiah, Rasheeduzzafar, Roger Baggott, Durability Requirements for Reinforced Concrete
Construction in Aggressive Marine Environments, *Marine Structures* 3 (1990) 285-300

[5] Joseph e. Bowles, Foundation analysis and design, fifth edition, Mc-Graw hill

[6] Landris T. Lee, Jr., and Richard W.Peterson,"Underwater Geotechnical Foundation", *US Army of Corps of Engineers, December 2001*

[7] Codes of practice excavation, government of Western Australia, commission for occupational safety and health

[8] NAVFAC MO-104.2,"Specialiez Underwater Waterfront Facilities Inspections", *Sn 0525-LP-173-0167, October 1987*

[9] Han Pardon Associates,"New York City Economic Development Corporation Waterfront Facilities and Maintenance Management System", *Inspection Guideline Manual, October 1999*

[10] Luca Bertolini, Elena Redaelli,"Throwing power of cathodic prevention applied by means of sacrificial Anodes to partially submerged marine reinforced concrete piles: Results of numerical simulations"

[11] L. Bertolini, B. Elsener, P. Pedeferri, R. Polder,"Corrosion of Steel in Concrete, Prevention, Diagnosis, Repair", *Wiley-VCH, Weinheim, 2004.*

[12] C.L. Page,"Corrosion and protection of reinforcing steel in concrete", in: C.L. Page, M.M. Page (Eds.), Durability of Concrete and Cement Composites, *Woodhead Publishing Ltd., Cambridge, 2007, pp. 156–186.*

[13] A. Bentur, S. Diamond, N. Berke, "Steel Corrosion in Concrete", *Fundamental and Civil Engineering Practice, E&FN Spon, London, 1997.*

[14] R.E. Melchers, C.Q. Li,"Reinforcement corrosion initiation and activation times in concrete structures exposed to severe marine environments*", Cement and Concrete Research*

[15] P.k.mehta, p.j.m.monteiro,"concrete microstructure, prosperities and material", chapter5

[16] M. Naderi and S. A. K. Mousavi,"Investigation of Some Properties and Durability of Concrete in the Urumie Lake".

[17] K. Lau, A.A. Sagues, L. Yao, R.G. Powers,"Corrosion performance of concrete cylinder piles"*, Corrosion 63 (4) (2007) 366–378.*

[18] A.A. Sagues,"Modeling the effects of corrosion on the lifetime of extended reinforced concrete structures*", Corrosion 59 (10) (2003) 854–866.*
[19] Wousk Ahn, Darrell Joque, and Amfinn Rusten,"A Study on Corrosion Resistance of Pre stressed Marine Concrete Piles", *corrosion 2003, page nomber03239*
[20] Building research establishments news, Her Majesty's Stationanery Office, London, winter 1979

[21] Haynes, H. H., "Permeability of Concrete in Sea Water" Performance of Concrete in Marine Environment*, ACI SP-65, edited by Malhotra, V. M., ACI, Detroit, MI, August 1980, pp. 22-38.*
[22] C. Ftikos, G. Parissakis,"A study on the effect of some ions contained in seawater on hydrated cement compounds", in: J.M. Scanlon (Ed.), Katharine and Bryant Mather International Conference on Concrete Durability*, American Concrete Institute,1987, pp. 1651–1665, S P (100).*
[23] Ahmad Shayan, Aimin Xu,"Performance of glass powder as a pozzolanic material in concrete: A field trial on concrete slabs*"*, *Cement and Concrete Research 36 (2006) 457–468 December 2005*
[24] A. Shayan ,A. Xu, G. Chirgwin, H. Morris*,"*Effects of seawater on AAR expansion of concrete*", Cement and Concrete Research", 40 (2010) 563–568*
[25] J.G. Wiebenga,"Durability of concrete structures along the North Sea coast of the Netherlands*"*, *American Concrete Institute SP65 (1980) 437–452.*
[26] A.A. Sagues,"Modeling the effects of corrosion on the lifetime of extended reinforced concrete structures", *Corrosion 59 (10) (2003) 854–866.*
[27] Mehta,P.P,"Performance of Concrete in Marine Environment", *ACI SP-65,pp.1_20,1980*