

MARINE ENVIRONMENT AND ITS ILL EFFECTS ON STRUCTURAL CONCRETE

Sabrina Islam¹, Md. Moinul Islam² and Md. Saiful Islam³

¹Department of Civil Engineering, Southern University Bangladesh.

^{2,3}Department of Civil Engineering, Chittagong University of Engineering and Technology (CUET),
Chittagong-4349, Bangladesh

*msislam@cuet.ac.bd, msislamcuet@yahoo.com

Abstract- As a universally recognized construction material, concrete has been used for the construction of various types of offshore / onshore structure over the several decades. The oceans and seas are large bodies of water covering nearly 80% of the total surface of the earth. Marine environment is not just over the sea but it can covers the area where concrete becomes wet with sea water and wherever the wind will carry salt water spray that may be as far as few kilometers inland. Sea water contains about 3.5% different soluble salts and depending on the tidal range, wave actions, nature, extent of deterioration process, the marine structures are subjected under the action of different zones. The splash / tidal zone is considered as the most corrosive area due to the continuous effect of the highly aerated sea water, salt water spray, temperature fluctuation, wave action etc. and the structural concrete here experiences the concentrated effect of building up of salt ions. These actions become predominate in presence of oxygen and carbon dioxide and make both the concrete and the embedded rebar vulnerable to damage / corrosion. Whereas submerged zone is known as the least corrosive area due to non-availability of O₂ and CO₂ although the rapid penetration of sea salts may be caused due to the large hydrostatic pressure.

Keywords: Durability, Marine environment, Sulfate attack, Chloride attack, Rebar corrosion

1. INTRODUCTION

The term marine environment is generally well understood but the complexities inherent in such an environment are not usually clear. Marine environment is not just over the sea, but it could be deemed to be extending over the coast and the neighborhood of tidal cracks, backwaters and estuaries [1]. Broadly, it covers the area where concrete becomes wet with sea water and wherever the wind will carry salt water spray which may be as far as few km inland [2]. Reinforced concrete structures, located in such an environment are always subjected to aggressive loading physical, mechanical and chemical in nature over their entire life span. It is, therefore, necessary to understand clearly the characteristics of the seas, the various aggressive agents causing distress, their nature, intensity of attack, the different detrimental zones etc. in order to get satisfactory performance of marine structures.

Sea water has a total salinity of 3.5 percent of which 78 percent of the dissolved salts being NaCl and 15 percent MgCl₂ and MgSO₄ [3]. On mixing, the chloride and sulfate ions react chemically with components of cement at early stages of hydration and yields expansive products such as ettringite and others. Mixing of sea water leads to slightly higher early strength but a lower long term strength of concrete. The loss of strength is usually not more than 15 percent and can, therefore,

often be tolerated. In case of reinforced and prestressed concrete, sea water increases the risk of rebar corrosion, the danger being greater in tropical countries.

In a marine environment, the structural concrete in the splash/tidal zone undergoes alternate wetting and drying process due to wave and tidal action. Alternate wetting and drying cycles gradually lead to a buildup of high concentration of salts at various depths which accelerates the process of chemical reactions causing an enhanced rate of deterioration of concrete in that location [4]. Moreover, concrete expands due to wetting while it shrinks during drying and in both the stage; the concrete mass undergoes volume changes. Due to this change in volume under physical constraints, internal stresses are developed resulting in the cracking of concrete.

Durability of concrete largely depends on the ease with which fluids both liquids and gases, can enter into and move through the concrete; this is commonly referred to as permeability of concrete. The movement of the various fluids through concrete takes place not only by flow through the porous system but also by diffusion and sorption. Nevertheless, the commonly accepted term permeability is generally used for the overall movement of fluids into and through concrete.

Because of the existence of pores of different size

some of which contribute to permeability and some do not do so. If the porosity is high and the pores are interconnected, they contribute to the transport of fluids through concrete so that its permeability is also high. On the other hand, if the pores are discontinuous or otherwise ineffective with respect to transport, then the permeability of the concrete is low, even if its porosity is high. Whatever the process of transport of fluids into concrete from the surrounding environment like marine environment the penetrated fluids containing objectionable salt ions react with the hydrated cement products and are reported to form expansive as well as leachable compounds which leads to the formation of micro cracks/porous cement matrix thereby opening new paths for the transportation of further harmful species into concrete. The ultimate result is the starting of deterioration process which may be ended by the rapid degradation/destruction of structural concrete.

2. CHARACTERISTICS OF MARINE ENVIRONMENT

The oceans and seas are large bodies of water covering nearly 80% of the total surface of the earth. Near the coast, the sea is divided into two regions, namely (i) continental shelf and (ii) continental slope. The continental shelf is a region having a gradual slope of typically 0.1° away from the beach face. Area wise, it covers about 7.5 percent of the world oceans and may extend up to 1500 km from the shore with an average width of 80 km. The average depth of the world continental shelf is 130 m although it may be extended up to a depth of 200 m. Beyond the continental shelf, the region namely the continental slopes, is characterized by a pronounced slope of typically 4° extending from the edge of the shelf down to abyssal depths.

(i) Salinity and Density:

The density of sea water is governed primarily by its salinity apart from the influence of temperature and pressure. In an open sea, a normal salinity of about 3.5% is found. Because of precipitation and evaporation and in some cases, the inflow of rivers and the melting of polar ice, salinity vary over the ocean surface. The average total concentrations of salts in different seas are given in **Table-1** [5].

Table -1: Average Salt Concentration in Different Seas

Sea	gm/liter	Percent
Mediterranean	38	3.8
Baltic	7	0.7
North sea and Atlantic	35	3.5
Black sea	18	1.8
Dead sea	53	5.3
Indian dwa	35.5	3.58

Fig.1 depicts the variation of temperature, salinity and density of sea water up to a depth of 300 m. The density is lowest near the surface, increases rapidly at the base of the mixed layer through the pycnocline and then usually increases slowly with increasing depth. However, the relative composition of sea water is more or less constant in most of the world's oceans because of the enormous

amount of mixing and circulation.

(ii) Temperature:

The variation in ocean temperature is less severe than that of the atmosphere. In moderate climates, variations are not likely to be of major structural significance. However, in more extreme climates, substantial vertical and lateral temperature gradients may exist. In the arctic, for instance, atmospheric temperature below -50°C may cool the upper part of the structure while beneath the ice line the lower part is relatively warm at around 0°C . The converse affect occurs in tropical areas with an upper temperature ranging from 35°C to 45°C and relative coolness beneath the sea.

(iii) Dissolved Gases:

All gases present in the atmosphere are found in the ocean. Of them, nitrogen, Oxygen and carbon dioxide are important because of their physiological importance in the life of marine plants and animals. Nitrogen varies from about 8 to 18 ml/liter of water and is saturated at all depths depending on temperature and salinity. The quantity of O_2 varies from about 5 to 10 ml/liter depending upon the plant and animal activity and its concentration is very important regarding corrosion of reinforcing steel in marine environment. The CO_2 concentration varies from 35 to 60 ml/liter of free CO_2 . Also the dissolved gases like CO_2 , SO_2 , H_2S etc. reacts with the hydrated cement products which reduces the reserve basicity of the pore solution thereby leading to initiation of rebar corrosion by electrochemical process. **Fig-2** depicts the distribution of temperature salinity and oxygen over depth.

(iv) Wave and Tidal Action:

In a marine environment, the waves may impose upto 200 million cycles of fully reversible loading on a structure in its life-span. In addition, these give rise to shock due to impact of breaking waves and the erosion of concrete surface by abrasion and cavitations. For example, in the North sea, the load from a single 25 m wave traveling at a velocity of 55 mph, is about 50,000 tons for a condeep structure [1]. Tide generation is due to gravitational attraction of the moon and the sun and the earth's rotation. The two primary effects of tidal variation are changes in water level and tidal currents. The changes in level causes alternate wetting and drying cycles to offshore structures and may vary from a few cm to as high as 16 meters depending upon the geographical location . However, alternate wetting and drying cycles help in building up of the harmful salt ions at the rebar level of concrete and initiates the electrochemical process of corrosion. The easily available atmospheric O_2 and CO_2 accelerate the corrosion process ultimately resulting in structural failure.

3. DIFFERENT ZONES OF MARINE STRUCTURES

Depending on the tidal range, nature, extent and mechanism of deterioration process, a structure exposed to marine environment, can be divided into different zones as shown in **Fig.-3**. These are briefly discussed below:

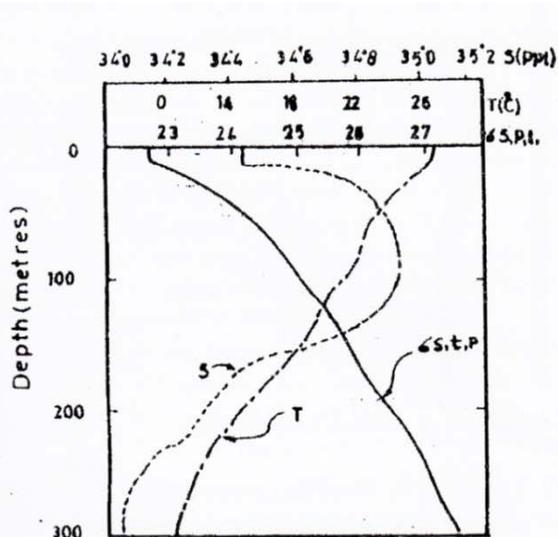


Fig.-1: Salinity-Temperature and Density Profile of a Section of an Ocean [6]

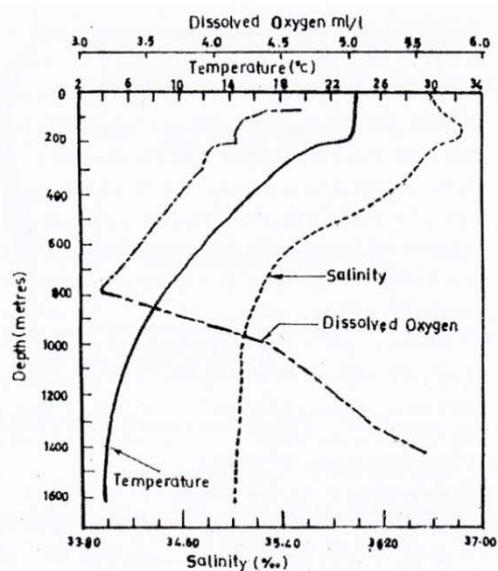


Fig.-2: Distribution of Temperature, Salinity and Oxygen over Depth [7]

(i) The Atmospheric Zone:

The atmospheric zone is the upper most zone or the marine environment and extends upward from the splash zone. In this zone, the air is heavily laden with moisture and contains substantial quantities of salts and gases. Winds are more frequent and stronger than on land, with velocity reaching upto 250 km/hour. The ambient temperature may range from 50°C in the Persian/Arabian Gulf to -45°C in the Arctic ocean. Due to temperature variation and wave action, freeze-thaw cycles also occur in this zone in some oceans.

(ii) Splash Zone:

The splash zone extends from some distance below the mean low water level (MLWL) to about 1.5 to 2 times the distance above the MLWL. The range depends on the local conditions of tide, normal wave height and ice abrasion in cold climates. According to Det Norske Veritas, the splash zone is defined as the astronomical tidal range plus the wave height having a probability of exceedence of 0.01. This is the most critical area for offshore structures due to the continuous contact with highly aerated sea water, erosive effect of salt water spray and wave action. These actions become predominant in presence of atmospheric O₂ and CO₂ and make both concrete and the embedded reinforcement vulnerable to corrosion.

(iii) Tidal zone:

This zone may be defined as one lying between the highest and lowest water levels reached by the waves with a statistical return period of six months when superimposed on the highest and lowest levels of spring tides. This zone experiences alternate wetting by sea water followed by subsequent drying in ambient air and is considered as the second most corrosive area. The temperature of the sea water within this zone ranges from a maximum of 30°C to a minimum of -2°C depending

upon the season or locality. The amount of dissolved oxygen in sea water in this zone is maximum i.e. about 7ppm.

(iv) Submerged Zone:

A major portion of an offshore structure consists of an immersed zone and is defined as that lying below the low water level and above the sea bed. Here the oxygen availability is minimum (about 3 ppm), but the hydrostatic pressures increasing with depth can cause rapid penetration of harmful salt ions into concrete. This is regarded as the least corrosive zone due to non-availability of oxygen and carbon dioxide that particularly accelerate the rebar corrosion process.

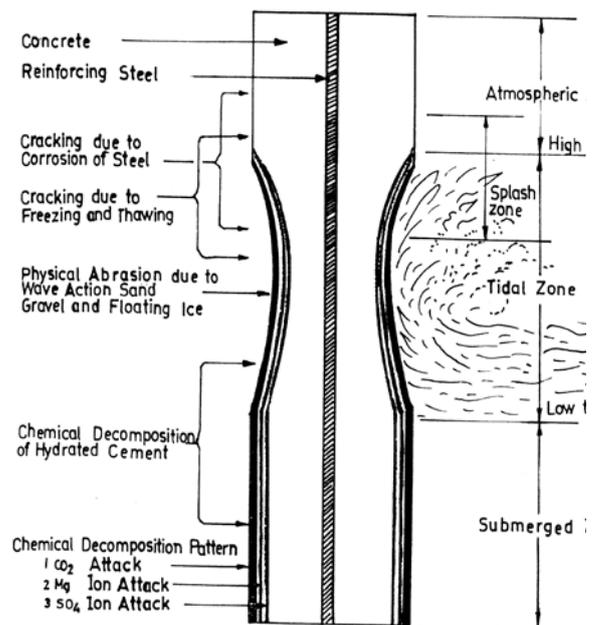


Fig.3: Deterioration of Concrete Structure in Marine Environment [1]

4. EFFECT OF MARINE ENVIRONMENT ON STRUCTURAL CONCRETE

For several reasons, effect of seawater on concrete deserves special attention. First, coastal and offshore sea structures are exposed to the simultaneous action of a number of physical and chemical deterioration processes, which provide an excellent opportunity to understand the complexity of concrete durability problems in practice. Second, oceans make up 80 percent of the surface of the earth; therefore, a large number of structures are exposed to seawater either directly or indirectly (e.g., winds can carry seawater spray up to few miles inland from the coastal). Concrete piers, decks, break-waters, and retaining walls are widely used in the construction of harbors and docks. To relieve land from pressures of urban congestion and pollution, floating offshore platforms made of concrete are being considered for location of new airports, power plants and waste disposal facilities. The use of concrete offshore drilling platforms and oil storage tanks is already on the increase.

Most seawaters are fairly uniform in chemical composition, which is characterized by the presence of about 3.5 percent soluble salts by weight **Table-2** show the average salt contents of sea water. The ionic concentrations of Na⁺ and Cl⁻ are highest, typically 11,000 and 20,000 mg/ liter, respectively. However, from the standpoint of aggressive action to cement hydration products, sufficient amounts of Mg²⁺ and SO₄⁻ are present, typically 1400 and 2700mg/liter, respectively. The pH of sea water varies between 7.5 and 8.4. the average value in equilibrium with the atmospheric CO₂ being 8.2. Under exceptional conditions (i.e. in sheltered bays and estuaries), pH values lower than 7.5 may be encountered; these are usually due to a higher concentration of dissolved CO₂, which would make the seawater more aggressive to Portland cement concrete.

Table -2: Salt Contents of Average Ocean Water [8]

Salt	Chemical Formula	Amount gm/litter	% of total salts
Sodium Chloride	NaCl	27.21	77.74
Magnesium Chloride	MgCl ₂	3.81	10.89
Magnesium Sulphate	MgSO ₄	1.66	4.74
Calcium Sulphate	CaSO ₄	1.26	3.60
Potassium Sulphate	K ₂ SO ₄	0.86	2.46
Calcium Carbonate	CaCO ₃	0.12	0.34
Magnesium Bromide	MgBr ₂	0.08	0.23
	Total	35.00	100.00

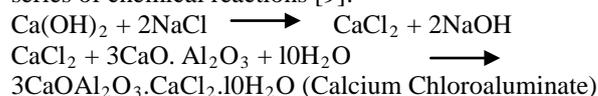
Concrete exposed to marine environment may deteriorate as a result of combined effects of chemical action of seawater on constituents of cement hydration

products, alkali-aggregate expansion (when reactive aggregates are present), crystallization pressure of salts within concrete if one face of the structure is subject to wetting and others to drying conditions, frost action in cold climates, corrosion of embedded steel in reinforced or prestressed members, and physical erosion due to wave action and floating objects. Attack on concrete due to any one of these causes tends to increase the permeability; not only would this make the material progressively more susceptible to further action by the same destructive agent but also to other types of attack. Thus a maze of interwoven chemical as well as physical causes of deterioration is found at work when a concrete structure exposed to seawater in is an advanced stage of degradation.

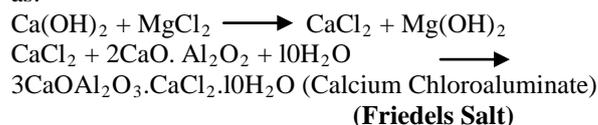
(i) Sea Salts attack on Concrete:

Marine environment is characterized by a typical aggressive loading. These loading are anionic compounds such as chlorides. sulphates and carbonates and are also due to cationic compounds such as alkali metals and magnesium. The action of principal chemical compounds, namely, sodium chloride, magnesium chloride, magnesium sulphate and calcium sulphate is explained, briefly below.

The process of chloride attack, sulphate attack and the action of dissolved CO₂ due to their presence in sea water on concrete may be explained by the following series of chemical reactions [9]:

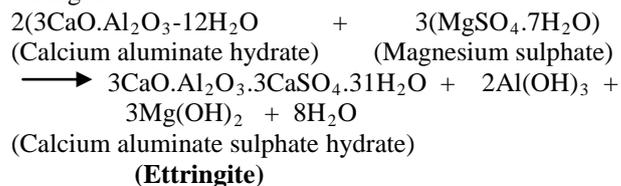


According to Mehta [1], MgCl₂ after reacting with Ca(OH)₂ of hydrated cement forms calcium chloride, which being soluble, gets leached out leading to material loss and weakening. The possible reaction can be given as:



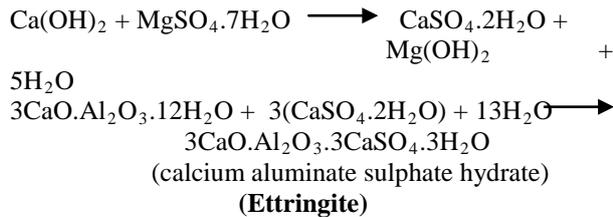
The calcium chloroaluminate known as friedels salt has a property of low to medium expansion. The formation of excess calcium chloride, which may leach out, results in increased permeability of concrete.

The magnesium sulphate reacts with hydrated C₃A and yields calcium aluminate sulphate hydrate, known as ettringite.

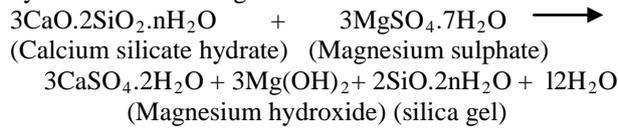


Magnesium sulphate also reacts with Ca(OH)₂, a hydration product of cement, and yields CaSO₄·2H₂O (gypsum) which in turn reacts with calcium aluminate hydrate to form additional calcium aluminate sulphate

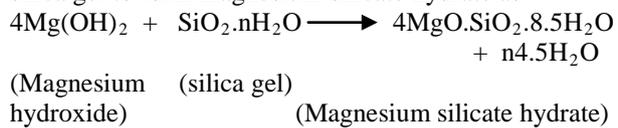
hydrate (ettringite) as below:



The magnesium sulphate also reacts with calcium silicate hydrate to form calcium sulphate, magnesium hydroxide and silica gel as follows:

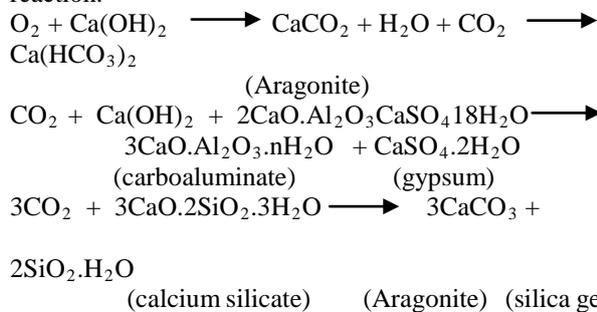


The $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (gypsum), thus formed can further react with calcium aluminate hydrate to form ettringite. The magnesium hydroxide can also have a reaction with silica gel to form magnesium silicate hydrate as



This magnesium silicate hydrate being a soft material, has low strength and affects the durability of concrete, as well.

According to Mehta, the effect of CO_2 on hydrated cement paste can be stated by the following possible reaction.



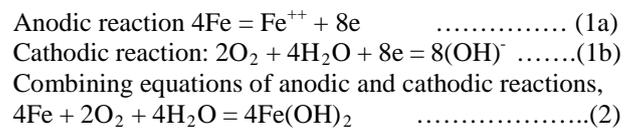
This results in a reduction of the pH of concrete which creates a favorable environment for the corrosion of the embedded reinforcement. Further, it is also mentioned that MgCl_2 and MgSO_4 combined with Ca(OH)_2 to form CaCl_2 and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) respectively, which being soluble in sea water, gets dissolved and leads to material loss and weakening. The formation of ettringite is associated with expansion and cracking.

Conversion of calcium silicate hydrate to magnesium silicate hydrate is associated with brittleness and loss of strength. Thus the detrimental effects associated with the chemical reactions manifest themselves as physical effects, such as volume change, weight change, change in permeability and in other properties. The loss of mass by surface wear and cracking has been shown to increase the

permeability of concrete, which then becomes the primary cause of one or more processes of chemical deterioration. Similarly, the detrimental effects of the chemical phenomena are physical, for example, leading of the components of hardened cement paste by soft water or acidic fluids would increase the porosity of concrete, thus making the material more vulnerable to abrasion and erosion.

(ii) Mechanism of rebar corrosion in Marine Environment:

The rusting of steel or more strictly the oxidation of steel is an electrochemical reaction that occurs at the anodic spots on the surface of the metal. Anodic and cathodic regions develop on the steel surface as a result of slight differences in the composition and state of the metal or variations in the conditions of the surrounding concrete. The reactions taking place are:



The ferrous hydroxide, thus formed, combines with excess oxygen to form iron oxide (Rust) and the fundamental chemical changes are shown in Fig.4 [10]

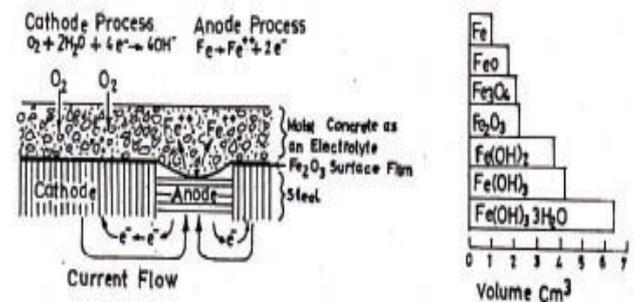


Fig.4: Expansion and Cracking of Concrete due to Corrosion of the Embedded Steel

But the concrete normally provides a high degree of protection to the embedded steel against corrosion due to a highly alkaline environment. The steel surface gets covered by iron oxide film which prevents further corrosion due to its passive nature. In addition, a lower water-cement ratio and well cured concrete has a low permeability which minimizes the penetration of corrosion inducing factors like chloride ions, corrosive gases like oxygen, carbon dioxide and water. The passivity is maintained as long as the defined amount of aggressive ions do not reach the steel surface. In a marine environment, the rebar corrosion is mainly initiated by the carbonation and chloride penetration process. The brief descriptions of the processes are as follows:

Carbonation Process:

The alkaline environment i.e. the higher pH value of the concrete may be changed by the ingress of acids from the surrounding environment. The acids are mainly CO_2 in air. Initially CO_2 will not be able to penetrate deeply

into the concrete because it will be bound within the surface layer by the basic reaction.



As a result of the P^{H} changes from (12-13) to neutrality

However, as the outermost portion of the concrete becomes carbonated, the CO_2 will ingress further and as soon as the P^{H} at the reinforcement is near neutrality, the passivation of the steel will be lost. The penetration depth is generally called the 'Carbonation depth' when exceeds the depth of cover to the reinforcement, the salt ions find a suitable environment leading to greater corrosion. The rate and depth of carbonation depends on the ambient R_H , the thickness and quality of the concrete cover. It is reckoned that concrete is most vulnerable to carbonation where R_H is between 50% and 75%. Because below 50% a moisture film does not form on the surface of the pores of the concrete, whilst above 75% the pores, being possibly blocked with water, do not provide ready access to the carbon dioxide.

Chloride Penetration Process:

Chlorides can be introduced into the concrete in two ways:

(a) as contaminants in the original mix and (b) as a result of post-setting exposure to de-icing salts, sea water or other chloride-bearing liquids. In marine environment, chloride ions from sea water gradually diffuses into the concrete with time leading to a condition when the concrete no longer able to protect the reinforcement from corrosion. Cavalier and Vassie [11] mentioned that establishing a universally applicable corrosion threshold concentration was difficult because, in a specific concrete, the threshold chloride level depends on several factors including P^{H} of concrete, water content, and proportion of water soluble chlorides. Combined with carbonation, even small chloride concentrations may depassivate the steel and accelerate the corrosion process. On the other hand, high chloride content shows very little evidence of corrosion for concrete submerged in sea water in sea water primarily because of the lack of oxygen.

Chlorides occur in concrete in three forms-chemically bound, physically adsorbed and as free chloride. Free chlorides are water soluble and responsible for initiation of corrosion. According to FHWA laboratory report, the water soluble chloride portion of concrete was found to be 75 to 80 percent of the total chloride presents [12].

(iii) Effect of Freeze-Thaw on Marine Concrete:

Freezing is a gradual process and depends on the rate of heat transfer, progressive increase in the concentration of dissolved salts in pore water and the pore size distribution. Fresh concrete contain a considerable quantity of free water and on freezing, discrete ice lenses are formed which expands about 9% volume. The increased volume of the ice lenses disrupts the fresh concrete causing nearly permanent damage to concrete. The fully hardened concrete is also vulnerable to frost damage, particularly to the effect of alternate cycle of

freezing and thawing. The severest condition for frost action rise when concrete has more than one face exposed to weather and in a position it remains wet for a long period.

It has been estimated that the freezing of water in the hardened concrete may exert a pressure of about 14 MPa which is large enough to exceed its tensile strength and consequently the damage occur [13]. The extent of damage varies from surface scaling to complete disintegration as ice is formed, starting at the exposed surface to the concrete and progressing through its depth.

In a marine environment, in addition to its presence in original mix, the chloride ion penetrates into the concrete either from sea water or sea winds carrying sea salts and reacts with the hydrated cement products which produces complex compounds including Friedels salt which are leachable and expansive in nature. The chloride attacks also destroy the passivity of steel and lead to the initiation of rebar corrosion. On the other hand, the penetration of sulphate ions attack the hydrated cement matrix with the formation of gypsum and a complex compound known as calcium sulphoaluminate (ettringite). Bogue [14] is of the opinion that the formation of gypsum hydrate causes an increase of 17.7% in volume. The action of principal sea salts namely NaCl , MgCl_2 , MgSO_4 and CaSO_4 on hardened concrete results in the formation of the expansive leachable compounds like Calcium chloroaluminate (Friedles Salts), Calcium aluminate sulfate hydrate (Ettringite), CaCl_2 etc. [8,9,10].

From the above discussion, it is clear that the structural concrete exposed to a marine environment with alternate freezing and thawing cycles faces twofold problems regarding deterioration. Stress resulting from the increased volume of freeze pore water and also from the expansive hydrated products caused by the action of sea salts. Detwiler *et al.* [15] assessed the durability of concrete in Freezing and Thawing examining the microstructure of the deteriorated concrete specimens with the help of scanning electron microscope and suggested to include microscopic examination. Wright *et al.* [16] carried out an investigation into methods of carrying out accelerated freezing and thawing test on concrete and showed that damage occurred more rapidly when specimens were frozen immersed in water than frozen in air although the rate of freezing was lower. Zamam *et al.* [17] studied the deterioration of concrete due to freezing and thawing and to deicing chemical use and showed that the visual estimation could be extremely misleading in terms of strength characteristics and maximum loss in strength was recorded for saturated solution. Chandra and Xu [18] studied the influence of pre saturation and F-T test condition on length changes of Portland Cement Mortar. It was seen that swelling depended upon the salt concentration gradient and was greater in dilute salt than in saturated salt solution.

(iv) Effect of large hydrostatic pressure on Marine Concrete:

The discovery of oil and natural gases in deep sea regions has given birth a plenty of offshore structures and also has drawn the attention of scientists and researchers to investigate the performance of structural concrete in such locations. With regard to technological requirements coupled with economic decisions, the advantages of using concrete in offshore structure has already been realized through the construction of numerous types of concrete gravity platforms including Condeep, Doris, Seatank, Andoc etc in the North Sea. In addition to concrete gravity platform, other types of concrete offshore structures are: Concrete cylinder pile supported structures, floatable/ bottom-founded concrete hull platform, concrete tension leg platform, deep draft concrete floaters and concrete production/ storage barges. The practical range of water depths for concrete gravity platform is considered as 40 m to 350 m [19].

The harmful sea salt ions enter the body of concrete at various depths under pressure [2] and start reacting with the hydrated cement products and the embedded steel. This results in disintegration of concrete which, in turn, increases its permeability and provides greater access to the detrimental ions for penetration inside. Burry and Domone [20] have shown that penetration of SW into concrete is a function of both the depth of water and time. Possible penetration would be about 75 mm at the end of 20 years at a depth of 26 meter and about 500 mm at a depth of 140 meters

Haynes et al [21] studied the SW absorption, compressive strength and permeability of high strength concrete at 0 m, 150 m and 6092 m depth of water. It was observed that concrete absorbed SW to greater extent at higher depths. The compressive strength of concrete increased and its permeability decreased with time. Brown et al [22] conducted tests on a number of concrete prisms containing mild steel bars immersed in SW in pressure cylinder under a pressure equivalent to 100 m head for one year. The test results indicated that although complete saturation by SW had occurred the rebar was still bright i.e. there was no trace of corrosion. Krishnomoorthy Kawadkar [23] have shown through their experimental investigation that pressure plays a significant role in the deterioration of cement concrete exposed to SW wherein chemical and morphological changes occur at a rapid rate.

5. CONCLUDING REMARKS

The marine environment is characterized by typical loading of various soluble salts and gases present in sea water. Serviceability and durability of marine structures depends mainly on the quality of concrete, depth of rebar cover and the exposure condition. Extensive investigations including survey of existing structures, both laboratory and field studies have been carried out on the devastating / ill effects of marine environment on structural concrete over the past decades. Some of the research outcomes / recommendation can be summarized below:

(a) The marine environment is characterized by typical aggressive loading of various soluble salts and gases present in sea water of which chloride and sulfate ions play the major role in the deterioration process. The corrosive ions of the penetrated salts react with the hardened cementing constituents and form some complex leachable / expansive compounds including CaCl, Friedel's Salt, ettringite etc. The effect of leachable compounds is the increased permeability while the expansive compounds can create enough pressure to develop cracks as the diffusion progresses.

(b) Of the various zones, splash zone is identified as the most corrosive area in a marine environment. Here the structural concrete suffers maximum damage due to concentrated effect / action of salt ions (as much as 3 to 6 times as that found in sea water) for continuous salt water spray, cyclic wetting and drying action, wave thrust, abrasion, freeze-thaw action, temperature fluctuation etc. in presence of O₂ and CO₂.

(c) The submerged zone is considered as the least corrosive zone due to in availability of O₂ and CO₂ although large hydrostatic pressure cause the rapid and deeper penetration of sea salts within structural concrete.

(d) In marine environment, the rebar corrosion is mainly initiated by the chloride penetration and carbonation process. For coastal / sea structures, carbonation is a non-critical phenomena than chloride attack due to quicker penetration and higher presence of chloride ions at rebar level which lead to a condition for initiation of corrosion. Particularly at splash / tidal zone due to availability of O₂ and CO₂, process of rebar corrosion accelerates and may easily lead to cracking, spalling and finally the structural damage.

(e) Establishing a universally applicable chloride threshold level for corrosion to initiate is very difficult as it depends on several parameters including pH of concrete, water content, proportion of water soluble chloride etc. It is observed to vary from 75 - 3640ppm of concrete.

(f) The penetration of chloride ions into concrete is greatly affected by its quality. A higher grade concrete associated with low w/c ratio and low permeability can limit the penetration of chloride considerably and tend to concentrate them on the surface.

(g) In general, durability of reinforced concrete in marine environment especially in splash / tidal zone mostly depends on the rebar corrosion rather than concrete deterioration. Due to high humidity, rebar corrosion is initiated by the presence of chloride ions and its amount controls the corrosion process. Higher grade concrete (>M40) having w/c ratio (≤ 0.40) with at least 50mm cover depth may ensure adequate durability in these zones.

References

- [1] Editorial, Concrete in marine environment, Indian Concrete Journal, pp. 357-358, Aug. 1990.
- [2] Geymayr, G. W., Repair of concrete in tropical marine environment, Performance of Concrete in Marine Environment, ACI Pub., SP-65, pp. 527-556, Aug. 1980.

- [3] Marshall, A.L., The marine environment, Marine Concrete, Van Nostrand Reinhold, New York, pp. 8-51, 1990.
- [4] Browne, R.D., et al., Deterioration of concrete structures under marine conditions and their inspection and repair, Maintenance of maritime structures, ICE, London, pp. 137-162, 1978.
- [5] Biczok, I., Concrete Corrosion, Concrete protection, Akademiai Kiado, Budapest, 1972.
- [6] Milligan, S., Effect of deep ocean environment on underwater installations, Conf. Proc. American Institute of Aeronautics and Astronautics, San Diego, Calif., March 1955.
- [7] Tuthill, A. H., et al., Guide-lines for selection of marine materials. Conf. Proc. Marine Technology Society, Washington, D. C., June 1965.
- [8] Myers, J. J., Holm, G. H., and Mc Allister, R. F., The Hand Book of Ocean and Underwater Engineering, McGraw-Hill, London, pp. 1094, 1969.
- [9] Ben - Yair, M. , The effect of chloride on concrete in hot and arid regions, Cement and Concrete Research, Vol. 4., No.3, pp. 405 - 416, 1974.
- [10] Islam, M.S., and Kaushik , S.K., An Experimental study on the behavior of reinforced concrete in marine environment, Ph. D Thisis, CE Dept., IIT Roorkee, April, 1994.
- [11] Cavalier, P.C., and Vassle, P.R., Investigation and repair of rebar corrosion in a bridge deck, Proc. ICE, London, V.70, pp. 461-480, Aug. 1981.
- [12] Durability of concrete bridge decks, National Cooperative Highway Research Program Synthesis 57. Transportation Research Board, Washington D.C., pp. 265-270, May-June, 1991.
- [13] M.S. Shetty, 'Concrete Technology Theory and Practice', 'Durability of Concrete, Chapter 9, S. Chand & Company ltd. Ram Nagar, New Delhi-110055, pp.304-3065,2002.
- [14] R.H. Bogue, 'Chemistry of Portland Cement', Reinhold Publishing Company, New York, 1971.
- [15] R.J. Detwiler, B.J. Dalgleish, and R.B. Williamson, 'Assessing the Durability of Concrete in Freezing and Thawing', ACI Material Journal, pp. 29-34, Jan.-Feb. 1989.
- [16] P.J.F. Wright, and J.M. Gregory, 'An Investigation into Methods of Carrying at Accelerated Freezing and Thawing Test on Concrete', Magazine of Concrete Research, pp.39-47, March 1955.
- [17] M.S. Zaman, P. Ridgway, and A.G.B. Ritchie, 'Predictions of Deterioration of Concrete due to Freezing and Thawing and to Deicing Chemical Use', ACI Material Journal, pp.56-58, Jan.-Feb. 1982.
- [18] S. Chandra, and A. Xu, 'Influence of Presaturation and Freeze-Thaw Test conditions on Length Changes of Portland Cement Mortars', Cement and Concrete Research', Vol.22, pp.515-524, 1992.
- [19] G. Raghava and A. G. Madhava Rao, "Concrete offshore Platforms - An overview, National Seminar on 'Use of concrete in offshore Structures, Docks and harbors', October 16-17, 1992, Roorkee.
- [20] M.R.C. Burry and P.L.Domone, " Role of Research in Design of Concrete Offshore Structures", 6th Annual OTC, Houston, Texas.
- [21] H.H Haynes and R.S.Highberg, " Concrete proprieties at Ocean depth", *J. Waterways, Harbour and Coastal Engineering Division*. Proc. ASCE, Vol.102, No. WW4, pp.455-470, Nov.1976.
- [22] R.D. Browne and P.L.J. Domone, "The long-term Performance of Concrete in the Marine Environment", *Offshore Structures*, ICE London, pp.49-59,1975.
- [23] S. Krishnamoorthy and K.G. Kawadkar, " Behavior of Cement Concrete in Sea Water under large Hydrostatic Pressure", *Int. Conf. on Ocean Engineering, INCOE 81*, Madras, India, pp.V-12/V-20, 1981.