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Performance Based Specifications for RC Structures in Indian Marine Environment

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Abstract - *Corrosion of reinforcement is the most significant cause of premature deterioration of reinforced concrete (RC) structures. Many of the concrete structures, which have been exposed to aggressive environments, suffer from durability problems and fail to fulfill their design service life requirements. India has a long coastline and the number of cities located in this coastal belt are witnessing premature deterioration. Under such conditions, chloride induced corrosion is expected to be the dominant mechanism for the determination of service life and hence, other deterioration mechanisms have been ruled out safely in the present study. In order to shed light on the nature of chloride ingress into concrete in a marine environment, concrete specimens have been exposed over a range of distances from the sea and the chlorides present in the atmosphere has been studied using the wet candle method. Today many owners require very long service for important concrete structures. As a part of this initiative, the existing standards and specifications across the world are reviewed. However, most standards do not give quantified guidance for designing for such long service lives. To ensure that concrete structures meet their service life requirement in marine environment, this study attempts to provide performance-based specifications for durability as prescriptive specifications do not adequately address quality concerns.*

Key Words: **service life, performance based specification, durability, wet candle, marine environment, chloride, corrosion**

1.INTRODUCTION

Concrete is considered to be the most widely used material after water. Despite the availability of vast information on good quality construction, a large number of reinforced concrete structures have undergone premature deterioration in the recent years. This has resulted in major repairs involving very high expenditures. The reasons could be poor quality of construction, poor anticipation of severity of exposure etc. As concrete consumes non-renewable material and emits 1 kg of carbon-di-oxide for every kg of cement produced, there is an urgent need to incorporate sustainability approach in the design of structures. One of the best ways to enhance sustainability of concrete construction is to enhance its durability and hence, the useful service life of the structure. The current practice of using certain prescriptive specifications to achieve long service life has many limitations because such specifications do not explicitly define what service life is and what constitute the end of service life. Therefore, modelling service life on the basis of performance has now become a necessity. Service life design can hence contribute to sustainable development by meeting the demands of the customers in an economic way and evade costly repairs due to substandard designs or over-design of structures from durability point of view.

Fortunately, the problems arising due to early deterioration of concrete structures are not much in India with respect to the western countries. However, due to India's long coastline, many structures located in the coastal belt are undergoing early deterioration. In such a scenario, the chloride induced corrosion is expected to be the dominant mechanism for the determination of service life and therefore, other deterioration mechanisms can be ruled out safely.

2. LITERATURE REVIEW

2.1 Environmental Characterization and Study of chloride penetration into concrete specimen

Roy et al. (1993) This paper discusses an experimental study. Five grades of concretes specimens were exposed in the atmospheric, tidal and submerged zones of a marine environment in Singapore and chloride profiles (chloride content v/s depth from the surface) were determined periodically. Few specimens were also added with super plasticizers to study the effects of admixtures and reduced water/cement on chloride penetration into concrete. A comparison was made between the determined chloride profiles and a chloride diffusion model and it was noted that there was good agreement between the two. Also, there was good agreement between the Chloride diffusion coefficient, D, calculated from the measured chloride profiles with previous data collected from surveys of structures located in the coastal areas and also from the laboratory tests. It was observed that D was mainly dependent on the water/cement ratio and did not change much with the addition of super plasticizers. Also, it was demonstrated that this method has the potential to produce a guideline in designing the required depths of concrete cover. Further, calculation of initiation time for corrosion of the reinforcement using chloride diffusion coefficient and equilibrium surface chloride level Cs has been briefly discussed.

Meira et al. (2007) This paper studies the relationship between chlorides in the marine atmosphere and chlorides penetrated into concrete structures at various locations in a marine atmospheric zone in a tropical region of Brazil. The study comprises of experimental work i.e. environmental characterization (climatic and chloride deposition data) and also the study of chloride ingress into concrete specimens exposed to marine atmospheric zone. As a standard procedure wet candle device was used to determine the amount of chlorides in the atmosphere captured on the exposed area of the device and therefore an experimental model to represent the correlation between chloride deposition on the wet candle device and the average total amount of chlorides penetrated into concrete is proposed. This correlation was determined as $C_{tot} = C_o + k_d\sqrt{D_{ac}}$, where k_d is a coefficient which is dependent on environmental and concrete characteristics, C_{tot} is the average total amount of chlorides penetrated into concrete, C_o is the initial chloride content in concrete before exposure and D_{ac} is the accumulated dry deposition of chlorides. For the environment where this research took place, k_d was found to be in the range 7×10^{-3} and 11×10^{-3} (% cement/$(g/m^2)^{0.5}$). It was observed that there were slight and consistent differences among concrete mixtures due to their porosity characteristics and their ability to bind chlorides.

Kulkarni (2009) This paper discusses some of the latest durability related provisions of the Canadian, European, North American and Australian codes, mainly describing the changes in the definitions of exposure classes and also the limiting values of the concrete properties for different classes. In line with international trend, this paper recommends changes in the definitions of exposure classes in Indian Standard IS 456:2000. These definitions have been made more elaborate and rational by aligning them to the anticipated degradation mechanisms. The recommended major exposure classes include: Corrosion (Cr), Carbonation penetration resistance (P) and sulphate attack (S). The exposure classes are further divided into 16 sub-classes. Also, for the new exposure classes, the limiting values for the properties of concrete are recommended and, in the process, the limiting values are kept more or less similar to those in the existing Indian standard IS 456:2000. It was noted that the limiting values recommended need to be validated with laboratory work such as accelerated tests on chloride-induced corrosion, carbonation, water permeability etc. Also, the need to update the corrosivity map of India was proposed.

Ramalingam and Santhanam (2012) This paper proposes a new environmental classification system considering various deterioration mechanisms for construction of concrete structures in India such as (i) Chloride induced corrosion (ii) Carbonation induced corrosion (iii) Sulphate and other chemical attack Within each classification system, the limiting values for concrete composition for achieving durability are specified along with the value of cover depth. The paper firstly describes the various limitations of the present system and later summarizes the developments across the world in exposure classification system. Concrete mix designs adopted in various construction projects across India executed by Central Public Works Department are then analyzed in the light of the prescriptions made by major codal agencies across the world. With the help of the analysis results and the developments in the exposure classification across the world, a rational system for classification of concrete exposure conditions is finally proposed. The paper also prescribes laboratory tests to verify the recommended limiting values of concrete properties. It was also noted that the new environmental classification system would lead to the implementation of performance specifications.

2.2 Performance Based Specifications for Durability

Poulsen (1995) This paper explains the method of determination of chloride profiles i.e. the grinding procedure for producing the powder samples, analysis of the chloride contents present in the powder sample and the interpretation of these observations. The paper also explains the method of reduction of chloride profiles into three parameters when the chloride penetration into concrete is caused by diffusion. Furthermore, the paper also explains the estimation of these parameters from the chloride profile. In this paper, the mathematical model of diffusion into a quasi-homogenous semi-infinite medium is proposed although the medium may not be quasi homogenous.

Lacasse and Vanier (1999) This paper has developed the durability design into a service life design based on reliability and on performances for reinforced concrete structures on the lines of structural design. It was observed that the present codes follow deem-to-satisfy method and performance of design is not explicitly formulated as service life. It was noted that design for durability should consider the probabilistic nature of aggressivity of environmental action, process of degradation and properties of materials involved. The aim of the DuraCrete project was to develop general guidelines for durability design, model the deterioration mechanisms, evaluate compliance tests for key parameters and quantify the various parameters in the deterioration models. The paper also brought to attention few problems such as uncertainty in aggressiveness of environment and characteristics of materials. Also, it was noted that cement producer could classify the material resistance in terms of Carbonation penetration coefficient D_{eff}, Chloride Diffusion coefficient D_o and Electrical resistivity to measure rate of corrosion ρ_o. Further few future developments were suggested such as development of mathematical models for frost, alkali-aggregate reaction and sulphate attack.

fib bulletin no. 34 – Model Code for service life design (2006) This code has identified existing durability models and outlined a framework for performance-based design. The objective of service life design as presented in this model is to establish a method to avoid deterioration due to environmental load like that of structural design present in the design codes. The design approach has been divided into four steps: Quantification of the deterioration mechanism, Definition of limit states, Determination of probability of occurrence of limit states and Definition of the type of limit state (SLS, ULS). Also, the service life design approach in this code has been elaborated for three different levels i.e. full probabilistic approach for exceptional structures, partial safety factor approach and deemed to satisfy approach. The Model Code has been classified into five chapters: General, Basis of design, Verification of service life design, Execution and its quality control and finally the Maintenance and condition control.

Wegen et al. (2012) This paper has presented a probability and performance-based design method for determination of combinations of 28 day chloride migration coefficient and cover depth that are needed to realise a specified service life. The guidelines presented in the paper meet the Dutch concrete standards. Target probability of failure was taken as 10 % for reinforced steel and 5% for prestressed steel. This paper explained the relevance of the DuraCrete approach for service life design of concrete structures in de-icing salts (XD) and marine environments (exposure classes XS). Rapid chloride migration test results were taken as the required performance of a particular composition of concrete, which was used in a semi-probabilistic method. The performance requirements were condensed in the form of tables indicating maximum values for RCM coefficient depending on concrete cover depth, type of cement, required service life and type of exposure. Further, it was realised that many parameters in the calculations contain large uncertainties and further study should be conducted to reduce the uncertainties.

Bhattacharjee (2012) This paper explained various service life related concepts, complexities involved in service life modelling and the shortcomings of the present service life models. Also, performance-based specifications for durability in Indian conditions was discussed. The author noted that durability provisions were only on the basis of some prescriptions. He also noted that the design can be made more economic by reducing the life cycle expenditure which also considers the maintenance expenditures. The author also observed that for modelling the profiles of moisture in different exposure zones of India, the uncertainties in the properties of materials must also be considered. Also, he made a note that the determination of chloride diffusion coefficient in laboratory will not yield accurate results as the conditions in laboratory are quite different from real time conditions where various influencing parameters act simultaneously. He also highlighted the under estimation in the measurement of the depth of carbonation by the phenolphthalein indicator. He is skeptical on the usage of Fick's diffusion model to predict cover depth and is of the opinion that prescribed cover depths by the experts are more reliable. According to him the codal provisions in IS 456:200 need modification and therefore proposed to take into consideration the importance of the structures, various tests like Figg's air permeability, water absorption etc. for prescribing recommendations on cover depth, choice of materials etc.

Bentz et al. (2014) This paper presented the comprehensiveness of commercially available modeling and simulation softwares such as Life-365, STADIUM, COMSOL Multiphysics etc. This paper describes the case where the service life is governed by the penetration of chloride ions into concrete and thereafter corrosion of rebars in RC structures. Some commonly used models were discussed considering real time problems. Also, the application of these models to appraise repair approach was discussed. The paper also compared the expected service life for concrete with three values of cover depth, addition of silica fume, addition of corrosion inhibitor and also the use of epoxy coated rebars. It was noted that the penetrated chlorides highly interact with the cementitious matrix by either being absorbed by CSH gel or react with aluminate phases to form Friedel's salt which indicate the importance of these processes in enhancing the service life of structures by slowing down the penetration. Also, it was noted that cracks are rarely taken into account in the models of service life and hence this paper had discussed the effect of the same in the prediction of service life.

3. METHODOLOGY

The first step in service life design is to quantify the environmental action and therefore classify the exposure zones. In this regard, Suvali beach, a coastal place near Surat, Gujarat was chosen to carry out the experimental research work. The experimental work is divided into two parts: (i) Characteristics of Environment and (ii) Studying chloride concentration in concrete specimens.

The second step is to determine the cover depth from chloride diffusion model for the different exposure zones. The details of both the steps are explained in the following sections.

3.1 Characteristics of Environment

The characteristics of environment further comprises of climatic and chloride deposition data. The following climatic data was obtained online

i. Local Temperature
ii. Relative Humidity
iii. Rainfall Data
iv. Average Wind Speed
v. Wind Direction

The chloride deposition rate is a parameter representing the presence of salts in marine atmospheric zone. In this study, the chloride deposition rate was measured at five monitoring stations placed at sites 50, 100, 300, 600 m from the sea so as to characterize inland transportation of atmospheric chlorides. At each station, a wet candle device was established as per the specifications of American Society for Testing Materials (ASTM) G140. Liquid samples from each wet candle device were collected periodically and determined for their chloride content by potentiometric titration with silver nitrate solution.

3.2 Studying Chloride concentration in concrete specimens

Twenty concrete specimen of 0.15 x 0.15 x 1.40 m was cast for two grades of concrete i.e. M20 and M35. These specimens were then placed at 50, 100, 300, 600 m from sea at the same monitoring stations. Concrete samples were then extracted at depths 10, 20, 30, 40 mm from the surface periodically from the specimens to obtain chloride profiles in concrete. For each sample, the total chloride content was determined by potentiometric titration with silver nitrate 0.1 N.

3.3 Determination of cover depth from chloride diffusion model

In order to determine the cover depth for RC structures for various exposure zones in the Indian marine environment, the following methodology was adopted:

i. The concrete samples were collected at three coastal places i.e. Suvali, Goa and Paradip, at various distances from the sea.
ii. The concrete samples were then determined for their chloride content in the laboratory by potentiometric titration with silver nitrate.
iii. The chloride profiles (chloride content v/s depth) were plotted and chloride diffusion coefficient determined by the method of surface tangents, the details of which are explained in the following section.
iv. Using the limit state equation for depassivation of reinforcement, the concrete cover depths were determined, the details of which are explained in the following section.
v. Finally, the cover depths obtained are consolidated in the form of table corresponding to the exposure classes defined for the Indian marine environment.

3.4 Limit State Equation for the depassivation of reinforcement

The modelling of corrosion caused by chlorides by full probabilistic design approach in uncracked concrete has been developed in the research project DuraCrete which was modified to some extent in the research project DARTS, each of which was sponsored by the European Union.

The following limit state function needs to be fulfilled:

$p\{\} = p_{dep.} = p\{C_{crit.} - C(a,t_{SL}) < 0\} < p_0$
$p\{\}$= probability of occurrence of depassivation
$C_{crit.}$ = critical chloride content (%)
$C(a,t_{SL})$ = chloride content at depth a and time t (%)
a = concrete cover (mm)
t_{SL}= design service life (years)
p_0 = target failure probability

In the limit state equation for the depassivation of reinforcement, a comparison is made between the critical chloride content C_{crit} and actual chloride content at the depth of the reinforcement at a time t C(x= a,t).

$$C_{crit} = C\,(x = a, t)$$
$$= C_o + (C_{S,\Delta x} - C_o)\left[1 - \text{erf}\,\frac{a-\Delta x}{2.\sqrt{D_{app,c}.t}}\right]$$

C_{crit}= Critical chloride content (%)
C(x,t): chloride content in the concrete at a depth x from the surface of the concrete and at time t (%)
C_o= Initial chloride content of the concrete (%)
$C_{S,\Delta x}$ = Chloride content at a depth Δx and at time t (%)
x = depth from the surface of the concrete (mm)
a = concrete cover (mm)
Δx= depth of convection zone (mm)

$D_{app,c}$= Apparent chloride diffusion coefficient (mm^2/years)
t = time (years)
erf = error function

The above model is on the basis of Fick's 2nd law of diffusion which takes into consideration that chloride transport in concrete is diffusion controlled in most observations. The surface of concrete is often exposed to alternate wetting and evaporation. This particular zone of the concrete is generally called "convection zone". The chloride transport into concrete in the convection zone is not diffusion controlled; hence, Fick's 2nd law of diffusion is not applicable in this zone. Therefore, the data of the convection zone is not considered and Ficks's 2nd law of diffusion is applied beginning at a depth Δx with a substitute surface chloride content $C_{s,\Delta x}$. Δx is the depth of the convection zone. By making this simplication, Fick's 2nd law of diffusion gives a good approximation of the chloride distribution at a depth x ≥ Δx.

3.5 Quantification of parameters

i. Critical Chloride Content (C_{crit})

The critical chloride content C_{crit} is defined as "The concentration of chlorides beyond which any further increase in concentration will result in depassivation of the rebar irrespective of whether the damage caused by corrosion is visible or not". The critical chloride content was taken as 0.025% by weight of concrete based on IS 456:2000 which recommends a limiting chloride content of 0.6 kg/m^3.

ii. Initial Chloride Content (C_o)

Apart from the chloride transported into concrete from the surface, the chloride content in concrete can also be caused by chloride contaminated water, cement or aggregates.

This becomes even more relevant in the case of marine structures where the chloride content of coarse and fine aggregates is considerable. Unlike the chloride profile due to chloride transported into concrete which decreases exponentially, the initial chloride content is assumed to be constant over the whole cross-section.

A value of 0.1 % by weight of cement was used based on data from concrete suppliers. This translates into approximately 0.004% by weight of concrete. It should be noted that there is no general consensus about the specific values for the initial chloride content and hence this value was used as a best estimate.

iii. Content of chlorides at the substitute surface ($C_{s,\Delta x}$)

The surface chloride content C_s and the substitute surface content $C_{s,\Delta x}$ at a depth Δx are dependent on environmental and geometrical conditions and also on the properties of materials such as binder type and the composition of concrete. $C_{s,\Delta x}$ was derived directly from the chloride profiles and the value was taken at a depth 10 mm from the surface for reasons of simplicity.

iv. Apparent chloride diffusion coefficient ($D_{app,c}$)

Generally $D_{app,c}$ is found out by "Chloride profiling method". $D_{app,c}$ is a constant mean value indicating the period from beginning of exposure to the moment of inspection when the profile is taken. The Chloride profiles can either be taken from test samples or existing structures. For the current study, chloride profiles were collected from different structures in different types of exposure in the marine environment whose exposure period was sufficiently long to collect genuine data. From the chloride profile graph, accurate estimates of C_i and C_s can be made. On the other hand, the estimate of D cannot be made without a geometrical estimate of the position of the tangent of the chloride profile at the exposed surface of the concrete.

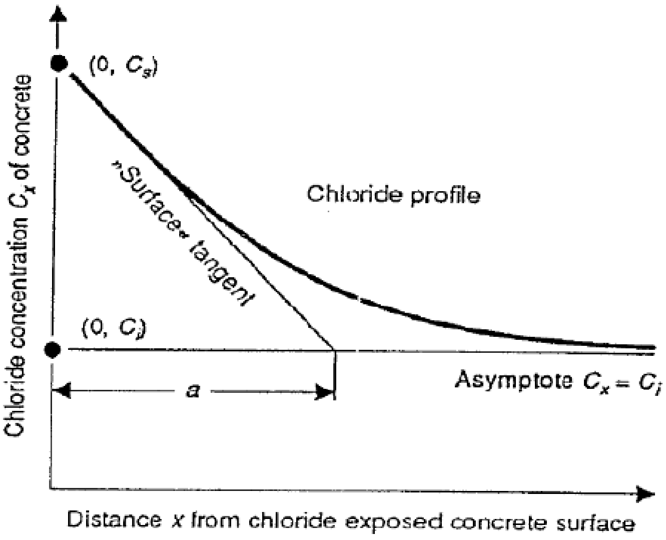


Fig -1: Method of surface tangent to determine $D_{app,c}$

The slope of the chloride profile at the point (x,C_x) is the partial derivative of the function modelling the chloride profile.

$$\frac{\partial C_x}{\partial x} = -\frac{C_s - C_i}{\sqrt{\pi.t.D}}\exp(-\frac{x^2}{4.t.D})$$

Thus the tangent of the chloride profile at the point (0,C_s) determines a line segment 'a' of the asymptote from the ordinate axis to the intersection between the tangent and the asymptote as shown in Fig -1.

The length of 'a' is:

$$a = \sqrt{\pi . t . D}$$

Therefore, the chloride diffusion coefficient D is determined as:

$$D = \frac{a^2}{\pi . t}$$

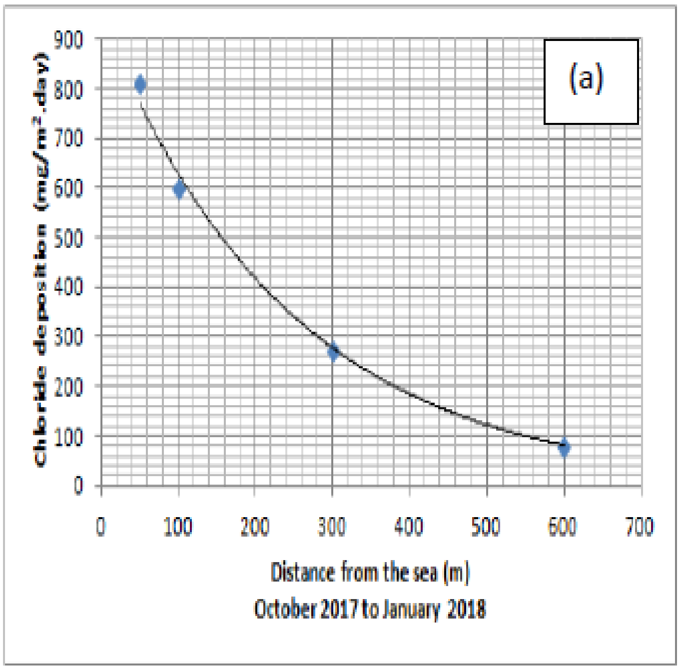
4. RESULTS AND DISCUSSIOS

4.1 Environmental Characterisation

The environmental characterisation comprises of climatic and chloride deposition data which has been obtained from the experimental research work conducted at Suvali, Gujarat the results of which have been presented and discussed under the following sub – headings: Climatic Data and Chloride concentration in concrete specimens.

i. Climatic Data

Suvali, Gujarat has a tropical climate. The summer commences in March and ends in June with the average high temperature being 37 °C. The relative humidity is generally between 60% and 80%. Heavy rainfall occurs in the months from June to September with a considerable increase in July. Monsoon retreats in the months of October and November with the return of high temperatures until late November. Winter begins in December and ends in late February, with average temperature of around 23 °C. Monthly average value of wind speed for the months of January to April ranged between 3.2 km/h to 4.5 km/h, 6.1 km/h to 7.7 km/h for the months of May to August and 2.2 km/h to 3.8 km/h for the months of September to December. Predominantly, the winds were from the quadrant S-W. The results of chloride deposition on the wet candle device for the period mid - October 2017 to mid- January 2018 and mid -January 2018 to mid – April 2018 are shown in Chart -1. The graph shows a clear fall off of atmospheric chloride content in the first meters from the sea and show a fall of in atmospheric chloride content in the range 85 % to 95 % in the first 500 m from the coastline. Therefore, an attempt has been made to classify the exposure classes in the Indian marine environment according to the trend exhibited by the atmospheric chlorides which exponentially decreases with the distance from the coastline. It should be noted that the exposure classes have been classified only with respect to chloride induced corrosion, it being the predominant deterioration mechanism in the coastal areas.



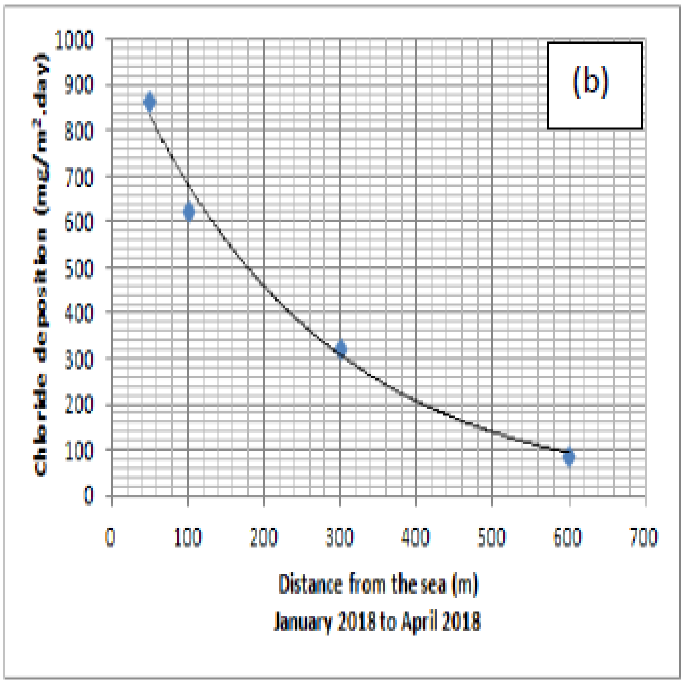


Chart -1: Chloride deposition on the wet candle device at 50, 100, 300 and 600 m from the sea

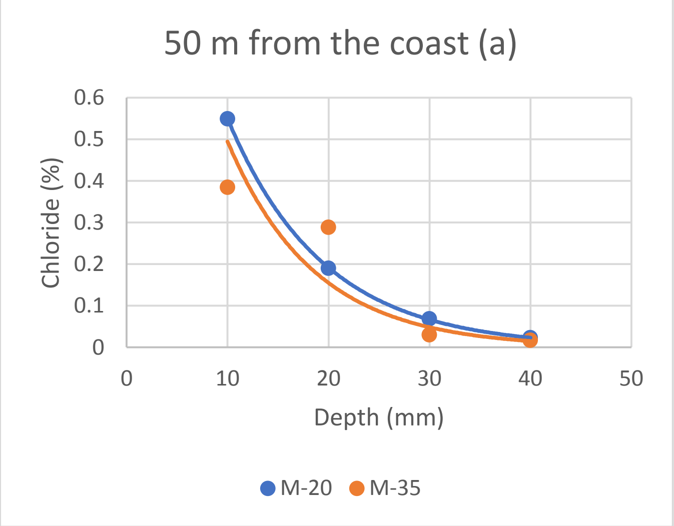
Table -1: Exposure classes for the Indian Marine Environment

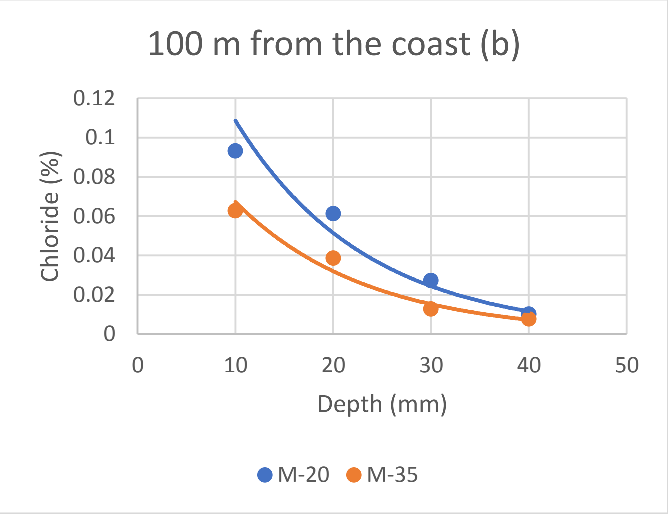
Exposure Classes for the Indian Marine Environment
Upto 100 m including Tidal Zone (Z1)

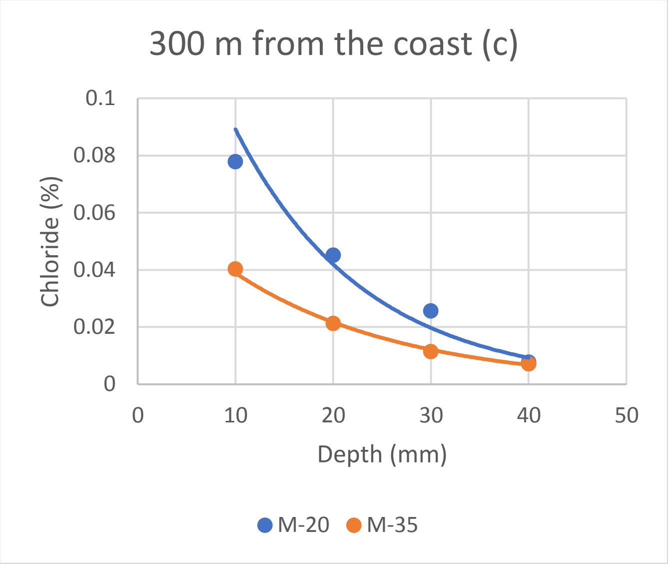
100 m – 600 m from the coast (Z2)
Beyond 600 m from the coast (Z3)

ii. Chloride concentration in concrete specimens

Chloride ingress in concrete specimens was found to be the lowest at 600 m from the coast. Also, the graphs clearly indicate the fall in chloride penetration with distance from the coast for both the grades of concrete. It is quite clear from the chloride profiles of exposed specimens of concrete as shown in Chart-2, that higher grade of concrete (M – 35) with a low water/cement ratio can reduce the chloride penetration in all the exposure locations by quite some extent. In general, the chloride penetration in the lower grade of concrete (M – 20) was about 1.3 to 2 36 times that of higher grade of concrete (M – 35) for same depth and period of exposure. This is directly related to the low permeability of higher grade of concrete (M – 35) arising due to low water/cement ratio. Generally, it was observed that the penetration of chlorides in concrete tends to increase with the time of exposure. Ionic diffusion is most likely to be the predominant transport mechanism with some contribution from absorption, particularly at areas near to the surface. Both the grades of concrete showed comparative pattern in the chloride profile with respect to the time of exposure as shown in Chart-2 and Chart-3.







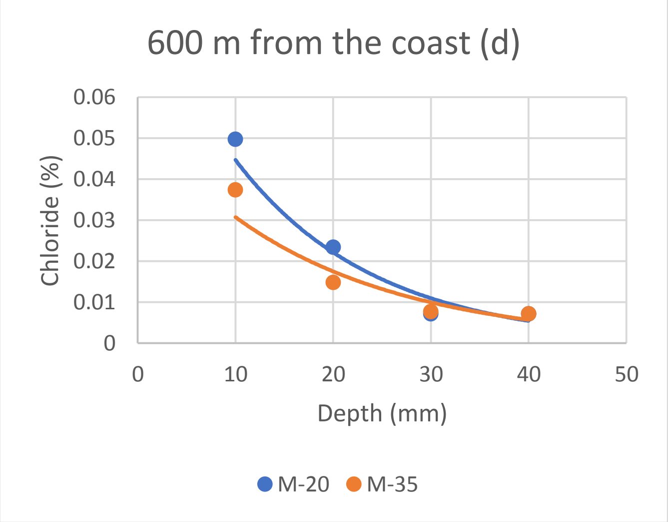
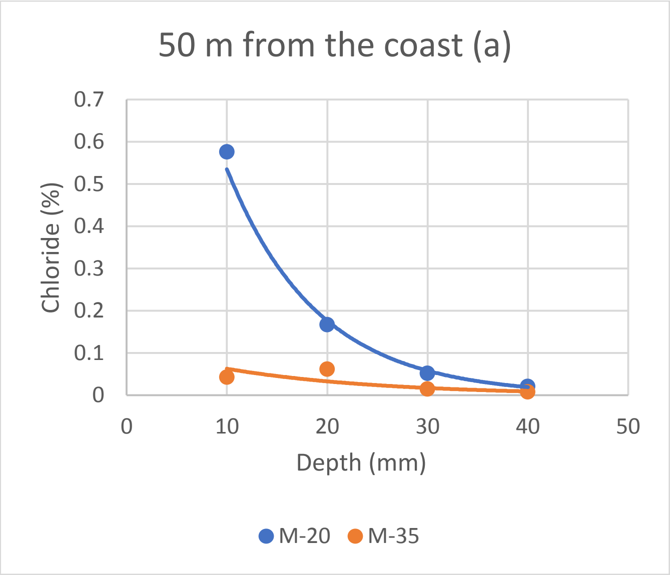
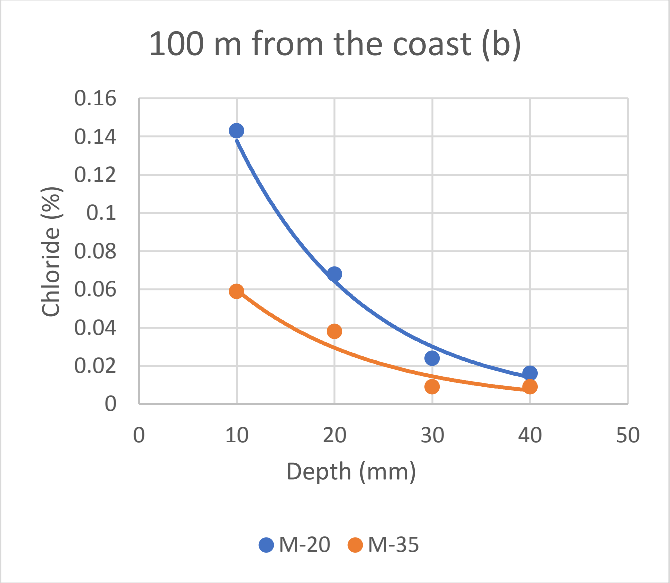
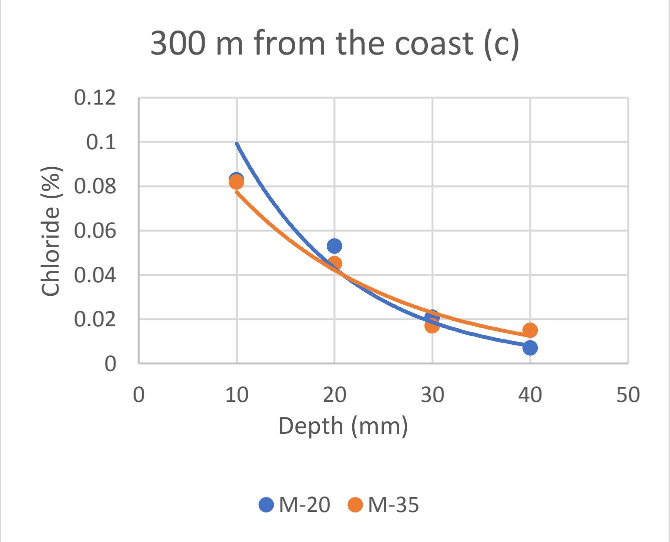


Chart -2: Chloride concentration profiles in concrete specimen at Suvali, Period of exposure: October 2017 to January 2018







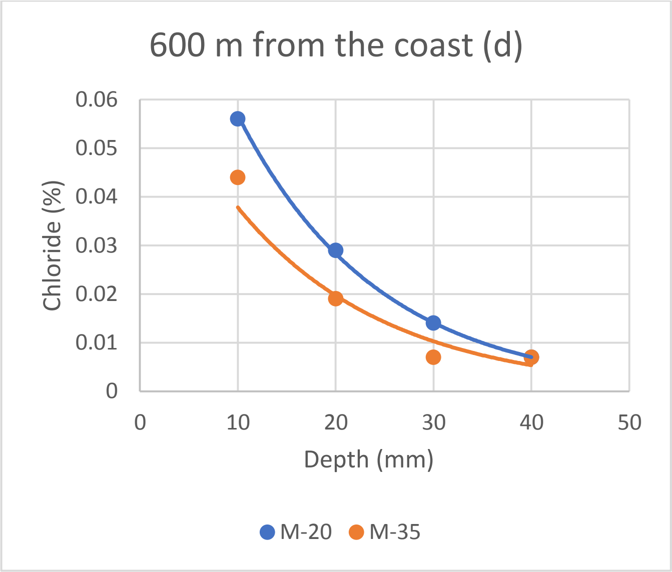
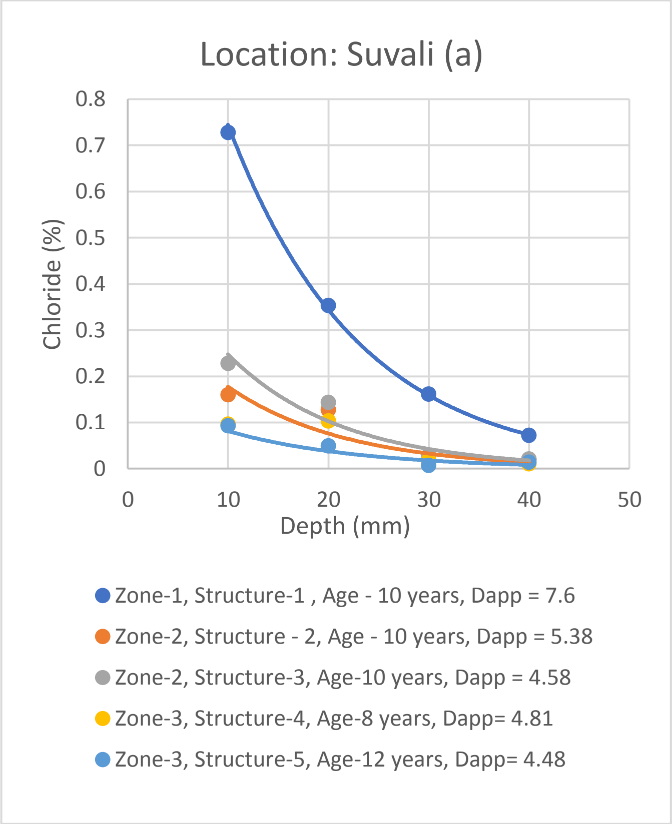


Chart -3: Chloride concentration profiles in concrete specimen at Suvali, Period of exposure: January 2018 to April 2018



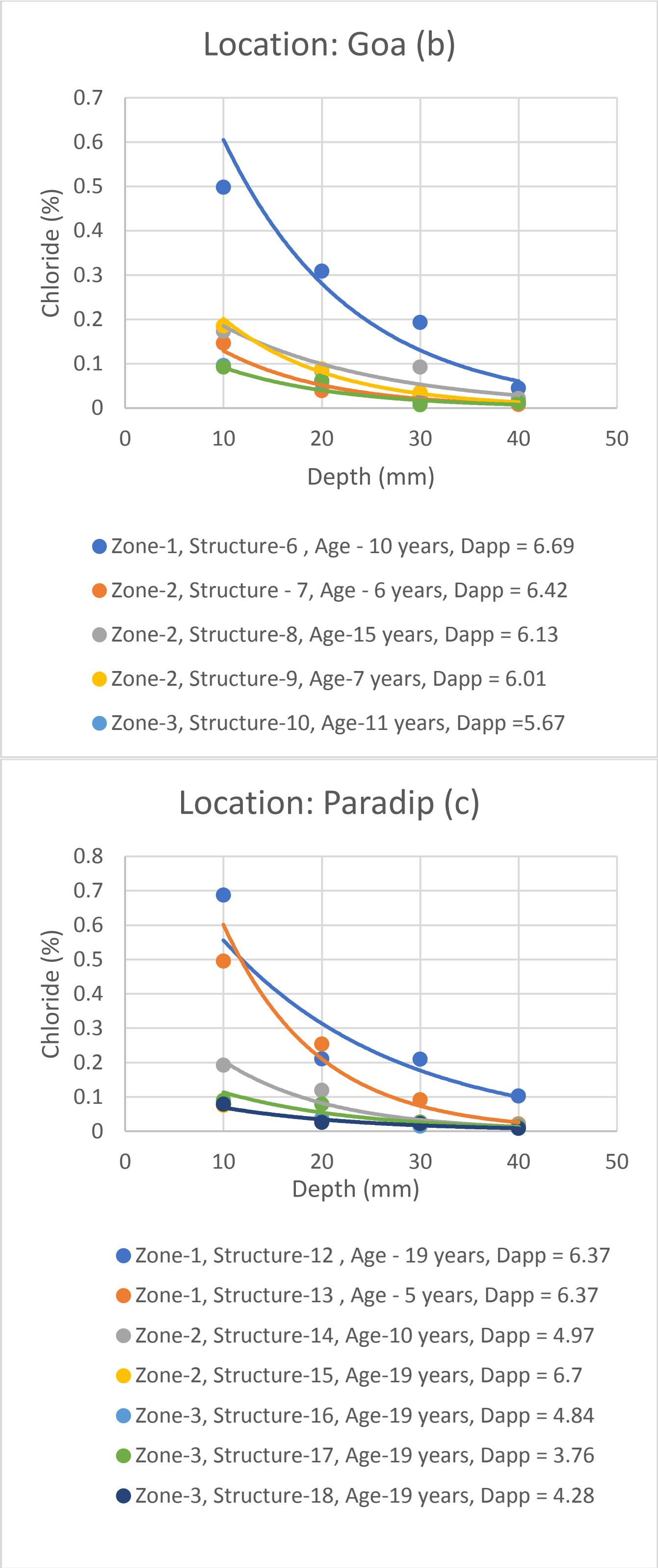


Chart -4: Chloride concentration profiles of RC structures in different exposure zones

4.2 Performance based specifications for durability

After obtaining the concrete samples from various locations in the three coastal places of India i.e. Suvali, Goa and Paradip, the samples were tested in the laboratory for their chloride contents and their chloride profiles (chloride content v/s Depth from the surface) plotted. Thereafter, apparent chloride diffusion coefficients were obtained graphically from the chloride profile graphs by the method of surface tangent. Subsequently, the Limit State equation for depassivation of reinforcement was used to determine the cover depths corresponding to each location. The chloride profiles and the determined values of apparent chloride diffusion coefficient are presented in the Chart-4.

4.3 Exposure classes for designing durable concrete

The cover depth obtained from the limit state equation for depassivation of reinforcement for various exposure zones have been consolidated in the form of table as shown in Table – 2. The mean of the cover depth is determined and therefore suggested for the corresponding exposure zones with an allowance Δc to account for the uncertainty in the quality of workmanship and quality of construction. This allowance can be typically between 5 mm to 15 mm as recommended by the British Standard BS 8500-1:2006. The specified cover is the minimum cover to the outer most reinforcement from the surface of the concrete member. For the sake of simplicity, a single value of cover depth is specified in the table although strictly the cover should be on the basis of the form of structural member like beam, slab, column, foundation etc. Nevertheless, the suggested cover can be suitably modified for example; the cover may be reduced for slabs and thin sections. Also, the cover can be reduced for higher grades of concrete.

5. CONCLUSIONS

Based on the study conducted, the following broad conclusions can be drawn:

i. Atmospheric chlorides which represent the chloride availability to deposit on the surface of the concrete and ingress into concrete can be studied using the wet candle method. However, as far as one can tell from literature, there is no such study conducted in India. Therefore, this study is a step in this direction.

ii. With limited period of exposure, it was concluded that chloride deposition on the wet candle device decreases with distance from the sea. It was observed that the chloride content in the lower grade of concrete (M – 20) was about 1.3 to 2 times that of higher grade of concrete (M – 35) for same depth and period of exposure. This is directly related to the low permeability of higher grade of concrete (M – 35) arising due to low water/cement ratio.

iii. Most codes across the world do not give quantified guidance to design for long service life. Since prescriptive specifications do not adequately address quality concerns, this study is an attempt to present a performance based design approach in determining cover depth to achieve a specified service life.

iv. Achieving the required service life for RC structures means delaying the initiation of corrosion of reinforcement. The most important components of the performance based approach are:

- Design limit state which is the onset of corrosion due to penetration of chlorides. Therefore, the propagation phase of corrosion is not considered and is therefore a conservative approach.
- The chloride load from the sea water drives penetration.
- The transport parameter i.e. the chloride diffusion coefficient.

v. In line with the definition of exposure classes in the international codes, this study has made an attempt to define three zones of exposure for chloride induced corrosion in marine environments. The suggested exposure zones are: Upto 100 m including Tidal zone, 100 m -600 m from the coast and Beyond 600 m from the coast. Furthermore, from the study conducted on concrete samples collected at coastal places, it is demonstrated that the diffusion model for chloride ingress can be used in the determination of concrete cover depth for RC structures for the various exposure zones as long as chloride diffusion coefficient, D, and surface chloride content at depth Δx are known for a specific structure in that particular environment.

vi. The distinct advantage of such classification is that the deterioration mechanism is considered and the value of the cover depth is suggested for the corresponding exposure zone. However, it should be noted that many parameters used in this study contain many uncertainties and therefore, further research should be conducted in order to reduce them.

Table -2: Suggested Cover Depth for the different exposure classes in the Indian Marine Environment

Zone	Cover Depth determined from the Limit State equation for depassivation of reinforcement (mm)							Suggested Cover Depth (mm)
Upto 100 m including Tidal Zone (Z1)	68	62	64	61	-	-	-	65 + Δc
100 m – 600 m from the coast (Z2)	46	46	48	49	47	46	38	45 + Δc
Beyond 600 m from the coast (Z3)	35	37	39	36	34	33	32	35 + Δc

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