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Assessment of some parameters of corrosion initiation prediction of reinforced concrete in marine environments

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Abstract. Chloride ion ingress is one of the major problems that affect the durability of concrete structures such as bridge decks, concrete pavements, and other structures exposed to harsh saline environments. Therefore, durability based design of concrete structures in severe condition has gained great significance in recent decades and various mathematical models for estimating the service life of rein-forced concrete have been proposed. In spite of comprehensive researches on the corrosion of rein-forced concrete, there are still various controversial concepts in quantitation of durability parameters such as chloride diffusion coefficient and surface chloride content. Effect of environment conditions on the durability of concrete structures is one of the most important issues. Hence, regional investigations are necessary for durability based design and evaluation of the models. Persian Gulf is one of the most aggressive regions of the world because of elevated temperature and humidity as well as high content of chloride ions in seawater. The aim of this study is evaluation of some parameters of durability of RC structures in marine environment from viewpoint of corrosion initiation. For this purpose, some experiments were carried out on the real RC structures and in laboratory. The result showed that various uncertainties in parameters of durability were existed.

Keywords: chloride Ion; concrete durability;corrosion initiation; marine conditions; durability modeling

1. Introduction

Concrete as the most widely man-made building material have been utilized in the construction industry for many years. In the past decades, usually, the designing of concrete mixtures were based on the compressive strength. Recently, in addition to this criterion, considering the durability aspects of reinforced concrete structures is required in most building codes, which is due to serious problems of reinforced concrete in harsh environmental conditions (Ramezanianpour and Miyamoto 2000, ACI 2000). One of the most corrosive conditions for the reinforced concrete in terms of durability is marine exposure. Damages caused by steel corrosion of structures constructed in marine areas result in extremely high rehabilitation costs annually (Ramezanianpour and Miyamoto 2000, Fib 2006).

Several factors affect on durability of reinforced concrete structures located in marine environment (Song *et al*. 2009). However, numerous studies indicate that the predominant reason of reinforced concrete deterioration is chloride-induced corrosion. If the amount of diffused

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chloride ions on the surface of the reinforcing bar reaches the threshold value, the steel bars embedded in concrete undergo depassivation and corrosion initiates. With propagation of corrosion, the corrosion products can expand more than 5 to 6 times of intact reinforcement. Subsequently, concrete cover deteriorates by cracking, delimitation or spalling (Poulsen and Mejlbro 2005). Previous researches show that over 90% of damages of structures located in the Persian Gulf and Oman Sea regions were due to chloride induced corrosion (Ashrafi and Ramezanianpour 2007). Construction of large ports in the coastal area of Persian Gulf and extremely destructive environmental conditions due to high temperature, humidity and high concentration of ions soluble in water have necessitated service-life prediction models for designing of durable RC structures (Ramezanianpour and Pourkhorshidi 2004).

Generally, in the present construction codes, deemed to satisfy provisions have been presented for durability issues of concrete structures. It means that the durability requirements for concrete structures are mostly based on the conventional method of specifying certain limiting values such as minimum cement content, maximum water-cement ratio, minimum cover thickness and maximum structural crack width. However, these codes give no guidance on how long a structure may remain in service.

In recent decades, several service life prediction models considering material characteristics and exposure conditions have been proposed by various researchers. Modeling the behavior of RC structures subjected to chloride attack with numerical solutions has been an interest of researchers since long time ago. The first service life prediction model of structures exposed to chloride ingress were proposed by Collepardi 40 years ago and during this period, models have been changed a lot in terms of structure, assumptions and solution methods (ACI 2000, Fib 2006, Ashrafi and Ramezanianpour 2004, Nilsson 2009, Shekarchi *et al*. 2008, Elishakoff and Miglis 2011). Despite the extensive research in this area, there are still many uncertainties. Therefore, several simplifying assumptions are used to model the process of chloride ions transfer into concrete (Marchanda and Samson 2009, Nilsson 2009, Poulsenand Mejlbro 2005). Currently computer software has also been developed to facilitate probability-based durability analysis and design using the Monte Carlo simulation method (Shin *et al*. 2011).

In this study, some important parameters of durability that affect on prediction models were evaluated by test on some real RC structures located in Persian gulf region. Additionally, some test was performed on samples that similar to concrete composition of structures in laboratory. Structures consist of five jetties that implement at different ages. Finally, corrosion initiation time was estimated by two famous and two local service life prediction models.

2. Structures and marine conditions

2.1 Weather condition of imam khomeini port

Imam Khomeini port is situated in the extreme northwest of Persian Gulf. This port is located in Khuzestan province in 160 km (99 Miles) of south-east of Ahwaz city. Imam Khomeini Port with area of 16.4 square kilometers (6.3 square miles) is one of the largest and most important commercial ports in Iran. The marginal areas of Persian Gulf due to their vicinity to the equator have high amount of the sun light and so the evaporation rate is high. Moreover, this region is considered as areas with hot and dry weather conditions. The region's average annual temperature is about 38℃ (100.4 ℉). Raining is limited in this region which is mostly during November and

December and there is almost no raining during summer. The average relative humidity of Imam Khomeini port about is 80 percent in the winter and is below 40 percent in summer (Ramezanianpour and Pourkhorshidi 2004).

2.2 Under investigation structures

The under investigation structures are five separate jetties located in the southern part of Imam Khomeini Port Complex having a similar mix design. These structures are constructed at different ages (2, 3, 4, 5 and 6years). Fig. 1 shows the location of structures and Table 1 represents the concrete mix design.

3. Experiments

In order to analyze some parameters of durability of RC structures in marine environment from view point of corrosion initiation, two series of experiments were performed. The first series was on concrete samples with similar concrete mix design of the structures with in laboratory (3 samples with same mixture design in laboratory) and the second series of the tests were performed on the in situ structures(3 samples from every point of structures in every ages).

3.1 Experiments in situ

The performed experiments on concrete structures included electrical resistivity via wenner test method (FM5-578 2004), concrete cover measurement and making powder from concrete at various depths of concrete to produce chloride ion profiles (ASTM C114 2010).

The experiments in each location were performed for both tidal and atmospheric conditions. The obtained chloride ion profiles are illustrated in Fig. 2. In addition, the apparent coefficient of diffusion (D_{app}) and surface chloride content (C_s) calculated from fitting the crank solution to the

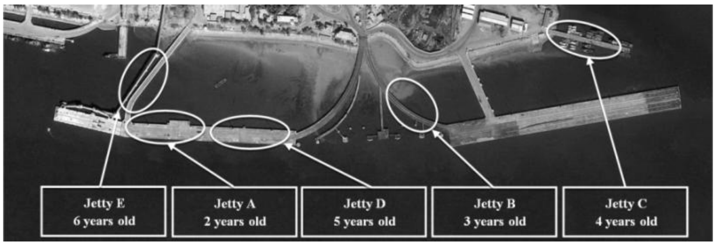

Fig. 1 Under investigation structures

Table 1 Concrete mix design

w/c	0.35
Cement type II [kg/m^3]	450
Silica fume [%](kg/m^3)	7% (31.5)
Fine aggregate [kg/m^3]	864
Coarse aggregate [kg/m^3]	866
Slump [cm]	10-12
SP [kg/m^3]	7

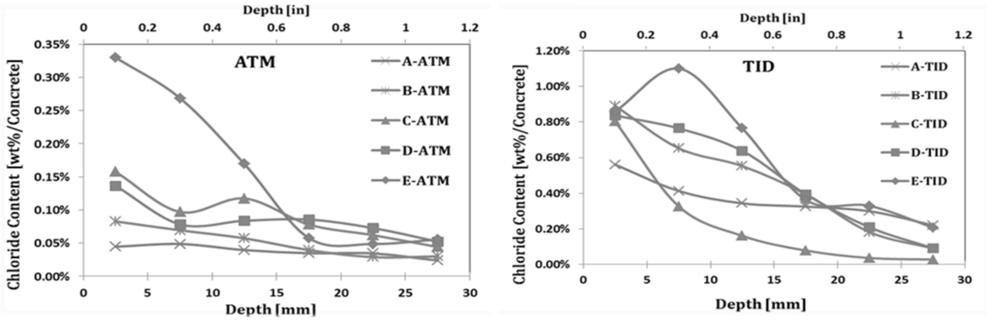

Fig. 2 Chloride profiles obtained from the structures

Table 2 In situ tests result

Sample code	Age	C_s [ii] wt%/conc	D_{app} [i] mm^2/years (in^2/years)	cover CoV %	cover mean mm (in)	Resistivity CoV% [iii]	Resistivity mean K.W. cm	Carbonation Depth mm (in)
A-ATM	2	82.65(0.1281)	0.06265%	34	5%	70.25(2.77)	1%	1(0.04)
B-ATM	3	49.47(0.0767)	0.09306%	48.5	n/a [iv]	71.5(2.81)	7%	3.5(0.14)
C-ATM	4	38.93(0.0603)	0.2199%	18.5	16%	74.2(2.92)	6%	6(0.24)
D-ATM	5	69.69(0.108)	0.1469%	33.5	12%	60.8(2.39)	5%	8.5(0.33)
E-ATM	6	15.31(0.0237)	0.402%	29	4%	38.9(1.53)	12%	9(0.35)
A-TID	2	237.9(0.3687)	0.5523%	10.25	31%	70.25(2.77)	1%	0
B-TID	3	53.13(0.0824)	1.008%	22	n/a	71.5(2.81)	7%	0
C-TID	4	12.91(0.02)	0.6847%	14.7	10%	74.2(2.92)	6%	0.5(0.02)
D-TID	5	27.91(0.0433)	1.227%	21.3	11%	59.1(2.33)	5%	2(0.08)
E-TID	6	20.68(0.321)	1.708%	29	n/a	38.4(1.51)	12%	3.5(0.14)

i Apparent Coefficient of diffusion
ii Surface chloride content
iii Coefficient of variation : which is the quotient of standard deviation to the mean value
iv Data for determination of CoV is less than enough

plot of chloride content versus depth are given in Table 2 (Crank 1975). The results of electrical resistivity and concrete cover measurement are represented in the same Table.

The codes A, B, C, D and E were applied for the structures with ages of 2, 3, 4, 5 and 6 years, respectively. Furthermore, the codes ATM and TID were used to indicate the atmospheric and tidal zones, respectively.

3.2 Experiments in the Lab

As mentioned before, the concrete mix designs made in the lab and the applied materials weresimilar to those of concrete structures. The experiments in the lab included RCMT (Rapid Chloride Migration Test) (NT Build 492) designed by concrete technology and durability research center at Amirkabir university of technology (Tehran polytechnic), RCPT (Rapid Chloride Permeability Test) (ASTM C1202 2010) manufactured by GERMANN instruments, Resistivity using wenner technique (FM5-578 2004, BS-1881 part 201) built by PROCEQ instruments (Resi)

Table 3 In lab test results

Test	RCMT [mm^2/years](in^2/years)	RCPT [Coulombs]		Resistivity [K.W.cm]		compressive strength [MPa](Ksi)
Standard method	NT-Build 492	ASTM C1202		FM5-578 BS-1881 part 201		BS-1881 part116
Result	169 (0.262)	1365	Low	36	Low	75.8(110)

and compressive test which were performed at the age of 28 days (BS-1881 part116). All specimens were cured according to ASTM C 192.The results of these experiments are shown in Table 3.

4. Analysis of the results

4.1 Laboratory studies

Results of tests on the concrete that is similar to the structure are evidences for considering durable concrete against chloride ion penetration of mentioned structures and all results are confirmed by their related code of practice in terms of durability.

4.2 Apparent diffusion coefficient

Diffusion coefficient is one of important parameters in estimation of concrete behavior in chloride ion transport into the concrete. This parameter is introduced based on assumption of the transfer of chloride ions into concrete and the govern equations are determined by Fick's laws. Researches indicate that the phenomenon of chloride ion transfer into the concrete can be occurred due to mechanisms of diffusion, penetration, capillarity, immigration and absorption. Most researchers in this field agree on the idea that the transfer of chloride ions into concrete is a combination of the mentioned mechanisms and diffusion mechanism can plays a dominant role in this phenomenon. Estimation of the behavior of concrete since 1970 has been mostly considered based on diffusion phenomenon and investigations on concrete also confirm the above fact. Diffusion coefficient is a constant parameter for the material but since concrete in the form of aliving organism still continues changing for many years after its construction, then this parameter is not also constant and generally can be changed over the time (Ashrafi and Ramezanianpour 2004, Collepardi *et al*. 1970, Ghosh *et al*. 2011, Growers and Millard 1999). Test results indicate that this parameter is also dependent on environmental exposure conditions, temperature and humidity. Equations governing the diffusion are based on Fick’s laws in the form of differential equation and can be solved in various forms. Some consider this equation as constant diffusion coefficient (crank solution) that is called apparent diffusion coefficient used for estimations. This assumption is considered as a close possible assumption for concrete with the age over 25 years. Some other researchers use the crank solution method but consider apparent diffusion coefficient as a factor that varies as time changes. They suggest that apparent diffusion coefficient does not essentially represent the absolute diffusion coefficient rather indicates average of what has happened to concrete that is suitable for estimation of the behavior of concrete against chloride ion transfer into the concrete. Some others analyze the Fick's law with time variable diffusion coefficient and practically use the Fick's law of this parameter in the initial conditions of differential equation. Finally, it is not possible to judge about it via obtained chloride ion profile. Hence, the apparent diffusion coefficient is considered in this study.

Past laboratory studies indicated this fact that apparent diffusion coefficient decreases over time and through progress of hydration process. Obtained results of chloride ion profiles represent this issue in a general case but by careful examination of the results it seems that this coefficient did not necessarily decrease under different conditions and sometimes even the apparent diffusion coefficient increases. This phenomenon can be investigated in the unknown behavior of concrete in different conditions and assumptions about calculation of the apparent diffusion coefficient. According to Fig. 3, the diffusion coefficient value for five years old concrete in comparison with 4 years old concrete can be observed in both atmospheric and tidal conditions. Regarding repetition of this event in both various conditions and also in other points, it can not be related just to the testing error. According to in place observations, protective surface coating used indifferent parts of the structure does not have the same quality and the surface coating will be weak for 5 years old concrete. This issue results in greater amount if diffusion coefficient than the expected rate. However, also determination of diffusion coefficient in different concrete ages by sampling from different parts of the structure, created at different time periods and consequently at different performance levels, leads to increased error that in return indicates inherent uncertainties of the problem.

Amount of electrical resistivity of the surface according to its mechanism can represent the amount of concrete's permeability that is useful for concrete evaluation in terms of durability, especially for in situ assessments (Growers and Millard 1999). In-situ resistivity tests procedure were based on RELM recommendations (polder 2000). Results of this experiment are too dependent on moisture of the concrete and materials used in the concrete. Fig. 4 represents changes of the results of this experiment in different ages of the concrete along with its values in the laboratory in the concrete age less than 28 days while it is expected that concretes with higher age will show greater electrical resistivity. The reasons for this issue can be found in the penetrated chloride ion because the chloride ions contained in concrete during the test causes increased electrical conductivity of the concrete and decreased electrical resistivity. Moreover, it seems that

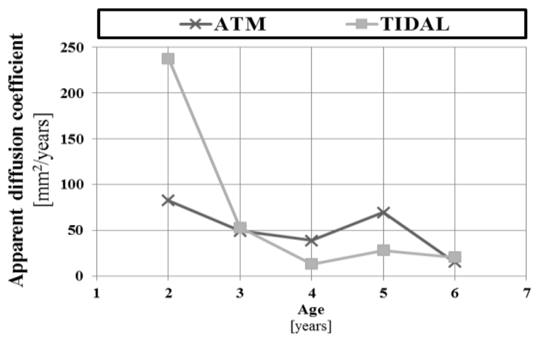

Fig. 3 Variation of apparent coefficient of diffusion

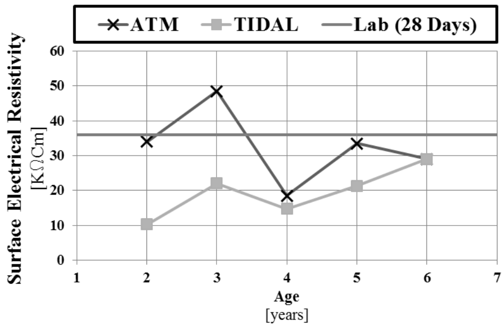

Fig. 4 Variation of surface electrical resistivity

permeability has increased in comparison with its 28-day's age while in reality it is different and concrete permeability decreases as its age increases. According to results of this test, it can be assumed that the amount of the effect of chloride ions on the electrical resistivity at early ages is greater than the effect of the development of hydration process and decreasing of concrete permeability. But when the age of concrete increases and rate of chloride ion penetration into concrete decreases (because of decreasing the permeability due to progress of hydration process), effect of increasing the age of concrete on electrical resistivity dominates comparing with effect of presence of chloride ions, and electrical resistivity increases as the age of concrete increases.

Laboratory studies show that electrical resistivity increases over the time that it is generally observed in the tidal conditions, but these values are highly variable for the atmospheric conditions due to lack of adequate moisture during the test. Because according to efforts made to obtain concrete moisture at the level of saturation, probably the generated moisture has not been enough. However, in the tidal conditions, in which concrete becomes wet twice a day, concrete has reached a good level of moisture. Among other causes of these errors, concrete construction at different periods with different levels of performance and also implementation of protective surface coating can be mentioned.

4.3 Amount of surface chloride ion

Amount of surface chloride ion is another important parameter in estimation of chloride ion transfer that is obtained after fitting of the equation of the Fick's second law. Extended researches related to estimation of this value indicate that amount of surface chloride on in addition exposure conditions of the chloride ion is also dependent on concrete type, and atmospheric and geometric conditions of the concrete (Angst *et al*. 2009, Ann *et al*. 2009). This issue makes its estimation more complicated. The amount of surface chloride for different ages of the concrete is shown in Fig. 5. According to investigations amount of surface chloride ion increases during the time and its value is different in various conditions. This issue is generally observed in the Fig. 5 in which most results are expectable, but in some cases some of the results are not. The reason can be considered more the used protective surface coatings as well as simple assumptions for determining their values according to obtained chloride ion profiles. It can be observed that chloride ion value is highly variable in the initial levels of concrete and generally it will be removed from chloride ion profile during fitting. This issue is one of the most important factors in making error and uncertainty in obtaining the parameter.

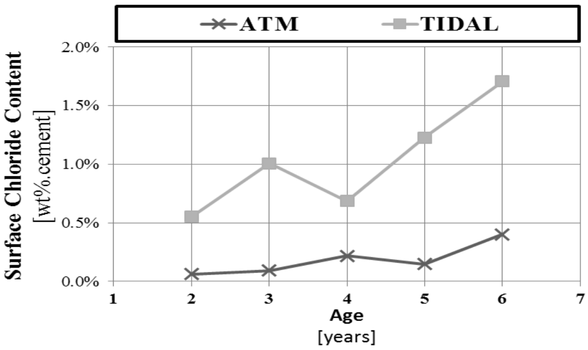

Fig. 5 Variation of surface chloride content

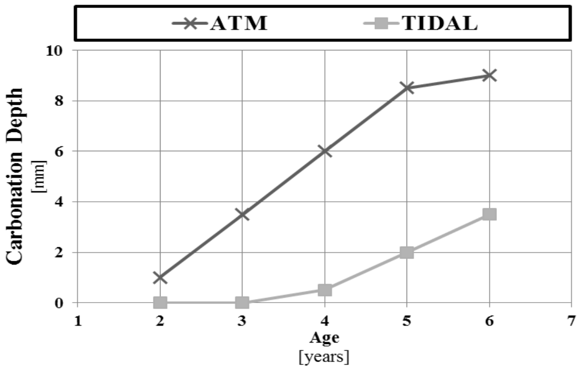

Fig. 6 Variation of carbonation depth

Table 4 Prediction of corrosion initiation time by models

	TIDAL ZONE	ATM ZONE
BHRC	15	-
DuarPGulf	66	193
Fib	6	22
Life-365	12	23

4.4 Carbonation depth

Carbonation causes two major events: one of them is reducing the alkalinity's concrete and the other one is effect of releasing bound chloride ions and guiding them into the concrete. If carbonation depth reaches the bar surface, then it will cause corrosion of the buried steel that needs too much time and is less important in the marine environmental conditions. Releasing of bound chloride ions due to carbonation, and ingress them into the concrete leads to creation of two zones form of the obtained chloride ions profile (Ramezanianpour and Porkhorshidi 2004). Generally, first zone (Convection Zone) and the related value of the chloride ion will be removed from chloride ion profile during fitting analysis. It is useful to investigate finding carbonation depth value to estimate this surface layer in which the Fick's second law cannot be applied (Fig. 6).

4.5 Estimation of the start time of corrosion

In this section, provided models are used to estimate the start time of corrosion for structure's concrete considering the zone weather conditions. These models include:

BHRC model

This non-probabilistic model is proposed by the concrete Technology and Durability Research Center (CTDRC) at Amirkabir University of Technology and the Building and Housing Research Center (BHRC) based on extensive tests performed in the Bandar Abbas, a port city in the Persian Gulf region (Ramezanianpour and Miyamoto 2000). The outputs of the model are the apparent diffusion coefficient as a function of time and the initiation time of corrosion. This model was analyzed for the concrete structures and the apparent coefficient of diffusion was calculated for 5 ages. The comparison of the model output with the values based on measured chloride profiles are given in Table 4. The results indicate the mismatch between estimated and measured results for different ages.

DuraPGulf model

DuraPGulf was proposed by the Construction Materials Institute at the University of Tehran based on the results of tests in a field exposure station located at Bandar Abbas City (Shekarchi *et al*. 2008). In this model, which is developed based on Fick’s second law of diffusion, material properties and environmental conditions are considered as parameters affecting service-life prediction. According to obtained results from this model, it seems that the estimated chloride contents obtained by this model are less than real amounts which make the concrete appear to be more resistant to chloride penetration. In addition, the estimated time for corrosion initiation by DuraPGulf model is more than the real time.

Life-365 model

The Life-365™ v1.0 program and manual were written by E.C. Bentz and M.D.A. Thomas under contract to the Life-365 Consortium I, which consisted of W. R. Grace Construction Products, Master Builders, and the Silica Fume Association. The Life-365™ v2.0 program and manual were written by M. A. Ehlen under contract to the Life-365 Consortium II, which consists of the Concrete Corrosion Inhibitors Association, the National Ready Mix Concrete Association, the Slag Cement Association, and the Silica Fume Association. This software designed to estimate the service life and life-cycle costs of alternative concrete mixture designs proportions and life-cycle costs of alternative concrete mixture designs proportions and corrosion protection systems. It follows research-based methodology developed by the Life-365 Consortium I and II groups of companies, that gives estimates on the effects of design, chloride exposure, environmental temperature, high-performance concrete mixture proportions, surface barriers, and steel types on the service life and life-cycle cost of steel-reinforced concrete structures.

The version 2.0.1 (2009) of software was used in this work. This model is based on extended studies of coastlines and ports of the USA. The local conditions can be specified in terms of temperature variation and surface chloride ion content. In addition, climatic information for different regions of the USA is considered as default in the available software. The model is based on the equation of Fick’s second law of diffusion and assumes concrete is saturated. The model determines the time for initiation of corrosion and adds a fixed propagation time of 6 years to present the service-life.

According to obtained results, the Life-365 predictions are close to the measured profiles. The proper performance of Life-365 can be the two-dimensional simulation of chloride diffusion, accurate solving of differential equation of Fick's second law of diffusion using the finite difference method and applying the actual diffusion coefficient (not the apparent coefficient of diffusion) as a function of time. The differences between model results and measured profiles could be owing to the difference between the materials properties and the environmental conditions used for developing the Life-365 model compared with those of the structures studied in the work.

Fib model

This model which is proposed in Bulletin 34 of the International Federation of Concrete (fib-Famous European Probabilistic Model), based on Fick's second law of diffusion in one dimension, was analyzed based on the Monte Carlo simulation method (with 100000 replications that it's lead to probability with ±0.0032) (Fib 2006, Robert 2009). In this model, the apparent diffusion coefficient is considered to be a function of time. The input parameters involved in this model include concrete properties, pozzolanic materials type and content, weather conditions and exposure condition. In addition, the apparent diffusion coefficient and the profile of diffused chloride ion into concrete are estimated in a probabilistic manner. The equations in the fib model consist of three main parts. The first part of the equations is related to estimation of the apparent diffusion coefficient based on the rapid chloride migration test (NordTest 1999), weather conditions, concrete mixture properties and time. The second part determines chloride ion content at a specified depth and the third part is for estimation of corrosion initiation time.

According to the results, it seems that the estimated chloride contents calculated by the fib model are greater than real amounts, which considers concrete less durable than it really seems. The fib model determines corrosion initiation time based on a reliability index of 1.3 or 10% probability. Therefore, the predicted initiation time of corrosion by this model is 22 and 6 years for atmospheric and tidal conditions, respectively (Table 4).

5. Summery and results

One of the elements of maintenance plan is analysis of life cycle. In this study, it is attempted to investigate the estimation of service life of reinforced concrete structures from the technical perspective. According to the studied results, it seems that durability parameters that are effective in the estimation of service life have been confronted strong uncertainty. On the other hand, the difference between laboratory results and the actual conditions remind us about this fact that what happens in the reality in the concrete structures will differ from what happens in the experimental results. It indicates that experimental results are valid only if be consistent with test results on the real structures.

According to the results of this study:

Values of the apparent coefficient of diffusion (D_{app}) in tidal zone are more than atmospheric zone and it seems that D_{app} in atmospheric zone is almost constant with age but in tidal zone D_{app} values decrease with age of concrete and seems that reduction continues up to 4 or 5 years. Values of surface resistivity also represented same results and it seems that the relationship between D_{app} and surface resistivity is established and it could be useful for economize the periodic durability investigation of concrete structures in marine. However, application of surface resistivity is dependent on the user's experience and also evaluation of chloride ion profile beside carbonation depth can be accurate in investigation of the current status of the RC structure.

Values of the surface chloride content (C_s) in tidal zone are more than atmospheric zone and it seems that C_s in both atmospheric and tidal zone is increase with age but rate of increasing in tidal zone is more than atmospheric zone.

Carbonation depths in atmospheric zone are more than tidal zone and it seems that these values in both atmospheric and tidal zone is increase with age but rate of increasing in atmospheric zone is more than tidal zone and it seems that in marine environment carbonation could not be the reason of the corrosion in tidal zone but for atmospheric zone carbonation could be destructive role and should be assess. In addition carbonation could release the banded chloride in surface and guide them into the concrete and also carbonation is the main reason of the disturbance of chloride content at the surface of concrete in chloride profiles.

Finally according to performed investigations it seems that making qualitative parameters out of qualitative parameters of durability is one of the most complicated stages of the modeling that generally has confronted strong uncertainties. It's reason can be related to unknown issues in the field of concrete that lead to too many simplifications, though problem of inherent uncertainty also makes it worse. Increasing number of tests performed on structures in the real conditions and using probabilistic approach in estimations can be mentioned as guidelines to reduce uncertainties.

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