KSCE Journal of Civil Engineering (2020) 24(1):131-142
DOI 10.1007/s12205-020-0793-8

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Durability of RC Structures against Carbonation-Induced Corrosion under the Impact of Climate Change

Mohammad Ghanooni-Bagha[a], **Mohammad Reza YekeFallah**[b], **and Mohsen Ali Shayanfar**[b]

[a]*Dept. of Civil Engineering, East Tehran Branch, Islamic Azad University, Tehran, Iran*
[b]*Dept. of Structural Engineering, School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran*

ARTICLE HISTORY

Received 19 May 2018
Revised 14 June 2019
Accepted 26 August 2019
Published Online 5 December 2019

KEYWORDS

Environmental factors
Carbonation
Corrosion
Monte Carlo
Operation conditions
Structural factors

ABSTRACT

The factors associated with concrete carbonation can be classified in three major categories of environmental factors, concrete's internal-structural factors, and construction-operation conditions. Climate change is expected to cause gradual change in many primary environmental factors, which may accelerate reinforcement corrosion in reinforced concrete (RC) structures. Studies show that CO_2 concentration in the atmosphere may rise from 379 ppm in 2005 to 1,000 ppm in 2100. Hence, adoption of suitable measures to protect exposed RC members against carbonation-induced corrosion is essential for countering the future environmental effects which, in turn, requires further investigation on the effect of critical structural factors, such as water-cement ratio and cement content in the concrete mix design, and construction-operation factors, such as concrete cover depth and surface protection, on the durability of RC members. In this study, these factors were investigated through Monte Carlo simulation. The results showed that slight adjustments in some structural and operational factors can significantly reduce the risk of corrosion initiation and ultimately improve the durability of concrete members against corrosion. The effect of each parameter on the probability of corrosion initiation during the design life of a RC structure was analyzed and interpreted using numerical examples.

1. Introduction

One of the serious issues regarding the use of RC structures is the possibly severe impact of environmental conditions on the corrosion of reinforcements leading to early and gradual structural degradation. Deficiency of our knowledge about the long-term performance of RC members and how it is influenced by environmental factors is of great concern (Basheer et al., 2001). The most important degradation mechanism of the exposed RC structures is the corrosion of steel bars by corrosive agents of the environments (Ghanooni-Bagha et al., 2018). Typically, the reinforcements corrode because of exposure to chloride or carbon dioxide (CO_2) and their corrosive effects in the presence of humidity and oxygen (Stewart and Rosowsky, 1998). This corrosion leads to concrete member damage through two mechanisms:

1. Corrosion reduces the cross section of rebars.
2. Corroded members often swell creating tensile stress in the concrete.

Because of this tensile stress, the reinforcement cover starts to crack and gets delaminated along the rebars, further damaging the member's integrity (Yoon et al., 2006).

High alkalinity of concrete's pore solution (12.5 and above) generally provides good protection against corrosion. This high alkalinity leads to creation of a passive layer on the rebar surface and inhibits the progress of active corrosion (Ghanooni-Bagha et al., 2016). However, degradation of the protective layer by aggressive ions (chlorides) or acidification (carbonation) of rebar environment can damage this passive phase (Poupard et al., 2006). A well compacted and cured concrete made with proper water-cement ratio will have a low permeability and good resistance against the penetration of corrosion initiators such as chloride, carbon dioxide, humidity, etc. The high electrical resistivity of the concrete may also limit the rate of corrosion by decreasing the electrical conductivity between anode and cathode zones (Shamsad, 2003). Also, the degree of saturation, as a determinant of concrete durability, and temperature, as a significant determinant

CORRESPONDENCE Mohammad Ghanooni-Bagha ✉ ghanoonibagha@iauet.ac.ir Dept. of Civil Engineering, East Tehran Branch, Islamic Azad University, Tehran, Iran

of electrical resistivity, play critical roles in this discussion (Gjørv et al., 1977; Østvik, 2005).

Global warming changes the temperature, humidity, and CO_2 concentration of the environment (Bastidas-Arteaga et al., 2009), which in turn increases the probability of corrosion in concrete structures (Wang et al., 2012). Global warming refers to how climate is affected by human activities such as excessive use of fossil fuels (coal, oil and gas) as well as large-scale deforestation, which lead to elevated accumulation of greenhouse gases like carbon dioxide in the Earth's atmosphere (Bastidas-Arteaga et al., 2009). As a result of climate change, the annual CO_2 concentration growth rate has increased from 1.4 ppm in 1960–2005 to 1.9 ppm in 1995 – 2005 (IPCC, 2007). Moreover, as mentioned, penetration of environmental CO_2 and chloride into a RC member accelerates the corrosion of its reinforcement. Empirical evidence also points to the effect of factors such as humidity, temperature and CO_2 (chloride) concentration on the penetration of CO_2 (chloride) into a concrete member (Saetta et al., 1993). Therefore, evaluation of the effect of climate change on the structural performance through the application of risk analysis methods to assess the environmental change induced degradation can be of great utility to structural design and maintenance (Bjarnadottir and Stewart, 2011).

In a series of studies, Shayanfar et al. and Kaveh et al. used meta-heuristic methods to determine the probability of rebar corrosion due to chloride diffusion and carbonation in RC structures (Kaveh et al., 2014; Shayanfar et al., 2015a; Shayanfar et al., 2015b; Shayanfar et al., 2016b). In another study, the effect of corrosion initiation on seismic performance of reinforced concrete frames were investigated (Ghanooni-Bagha et al., 2019). Shayanfar et al. also investigated the effect of corrosion of longitudinal rebars on the compressive strength of concrete in RC structures (Ghanooni-Bagha et al., 2016; Shayanfar et al., 2016a).

Similarly, Bastidas-Arteaga et al. (2010) presented a probabilistic method for assessing the effect of global warming on chloride diffusion, but this method is entirely focused on the initiation of corrosion (Akiyama et al., 2010). Also, Tuutti (1982) presented a model for chloride diffusion into a concrete member, but this model has some flaws that lead to error in modeling of chloride diffusion. Corrosion of reinforcement is a factor of chloride concentration at the surface of concrete member as well as other factors such as diffusion of chloride into concrete, aging of concrete, and its exposure to temperature and humidity variations (Val et al., 1998; Ababneh et al., 2003).

Furthermore, estimation of CO_2 diffusion risk and the efficacy of different preventive and protective measures against CO_2 diffusion has been the subject of many studies. Some of these studies have also assessed the effect of climate change on structures in specific locations (e.g., Stewart et al., 2011; Stewart et al., 2012; Wang et al., 2012). Several other studies have analyzed the effect of climate change on the corrosion of reinforcements and thus on degradation of RC structures in Australia. In these studies, degradation has been evaluated by an approximate method, which also accounts for climate change (Talukdar et al., 2012). These studies reported that at the current CO_2 concentration level (about 380 ppm), the probability of carbonation-induced corrosion is very low (Stewart and Rosowsky, 1998; Sudret et al., 2007). But clearly, with the rising level of CO_2 concentration in the atmosphere, there is a good chance of change in this condition. In another study, FIB Bulletin 34 has modeled the probability of structural degradation due to carbonation-induced corrosion (FIB, 2006). But in this model, CO_2 concentration was assumed to increase linearly at a rate of 1.5 ppm per year until reaching 500 ppm over a period of 100 years. This is while some studies predict that CO_2 concentration will reach to as high as 1,000 ppm in the future (IPCC, 2007).

Stewart et al. (2012) stated that CO_2 concentration is 5 – 10% higher in urban areas than that in rural environments, although this statement seems to be inaccurate. They also reported that the main sources of CO_2 production in urban areas are the vehicles that run on fossil fuels (Stewart et al., 2012). Moreover, they assessed the effect of climate change on CO_2 and chloride concentration and the consequent effect on the durability of RC structures. For this purpose, they first introduced the processes that contribute to degradation of RC structures through chloride or CO_2 diffusion (Bastidas-Arteaga et al., 2013), and then developed multiple models to assess the factors that are influenced by climate change, and are effective on degradation of RC structures (temperature, humidity and carbon dioxide concentration). Although this article has recommended solutions such as the use of stainless steel rebars, surface coating, thicker concrete cover, and the use of special concrete as the cover, it has not analyzed the impact of these solutions on the onset of corrosion and the ensuing degradation of RC member (Bastidas-Arteaga et al., 2013).

In another study, Stewart et al. (2011) assessed the reliability coefficient of RC structures under the effect of climate change up to the year 2100 (Stewart et al., 2011). In this study, the models were developed based on temperature and humidity of Sydney, Australia (temperate climate) and Darwin, Australia (tropical climate), and the results showed that in warm and dry regions of Australia, CO_2 diffusion can increase degradation probability by up to 400% (Stewart et al., 2011).

As noted above, the effect of climate change on CO_2 diffusion into RC structures and the effect of carbonation on the bearing capacity of RC members have been previously studied. The exiting literature on this subject provides several solutions for mitigating the probability of degradation in RC members and improving their resistance against corrosion. However, the effects of each solution on the corrosion resistance of RC members, corrosion initiation, and ultimately the durability of RC structures need to be investigated by numerical modeling and risk analysis methodologies. For example, numerical investigation of the effect of water-cement ratio on the durability of concrete member can contribute to mix design adjustments necessary for achieving concrete structure with greater durability under future conditions.

2. Modeling of CO_2 Diffusion into a Concrete Beam

In the presence of humidity and oxygen, diffusion of atmospheric

CO_2 into concrete leads to production of carbonic acid and reduction of concrete alkalinity (pH). Corrosion begins when carbonation depth becomes as large as concrete cover depth. or to put it differently, when CO_2 reaches the surface of rebars and their protective layer starts to deteriorate (Shayanfar et al., 2015b). The carbonation depth (Xc in cm) can be calculated by Eq. (1) (Bastidas-Arteaga et al., 2013).

$$X_c = \sqrt{\frac{2D_{CO2}(t)}{a} k\ C_{CO2} t \left(\frac{t_0}{t}\right)^{n_m}} \tag{1}$$

In the above formula, C_{CO2} is the concentration of CO_2 in the environment (in kg/m^3 multiplied by 10^{-3}), K is the factor of adjustment for variation of CO_2 concentration in different environments (Stewart et al., 2011), n_m is the concrete age factor incorporated to account for the ambient temperature variations (Bastidas-Arteaga et al., 2013), and t_0 denotes the first year. CO_2 diffusion coefficient D_{CO2} (t) and a can be obtained from Eqs. (2) and (3), respectively.

$$D_{co2}(t) = D_1 t^{-n_d} \tag{2}$$

In Eq. (2), D_{CO2}(t) is the time-dependent coefficient of CO_2 diffusion into concrete (Stewart et al., 2011). n_d is a dimensionless constant, and D_1 is the CO_2 diffusion coefficient of one year old concrete member. Both n_d *a*nd D_1 vary with water-cement ratio. The values of these parameters at 20°C and 65% humidity for different water-cement ratios are presented in Table 1 (Bastidas-Arteaga et al., 2013). As it can be inferred from Eq. (2), CO_2 diffusion into concrete decreases with time.

$$a = 0.75 C_e CaO \alpha_H \frac{M_{CO2}}{M_{CaO}} \tag{3}$$

$$\alpha_H = 1 - e^{-3.38 w/c} \tag{4}$$

In Eq. (3), C_e is the amount of cement used in making concrete member (in kg/m^3) (Bastidas-Arteaga et al., 2013), CaO is 0.65 (Stewart et al., 2011), α_H is the degree of hydration, obtained from Eq. (4) (Yoon et al., 2007). M_{CaO} and M_{CO2} are 56 and 44 respectively (Bastidas-Arteaga et al., 2013). In this formula, w/c denotes the water-cement ratio (Stewart et al., 2011).

Table 1. n_d and D_1 for Different Water-Cement Ratios (Bastidas-Arteaga et al., 2013)

W/C	$D_1 \times 10^{-4}$ cm^2 s^{-1}	n_d	α_H
0.45	0.65	0.218	0.78
0.50	1.24	0.232	0.81
0.55	2.22	0.240	0.84

Equation (1) is based on the assumption of constant CO_2 concentration, thus it cannot be applied for the scenarios where this concentration is increasing. To use this formula for such scenarios, it must be adjusted with a conservative estimate of CO_2 concentration, that is, the peak forecast of CO_2 concentration over the lifetime of concrete member. This adjustment can also be made based on an optimistic estimate of CO_2 concentration, which is the lowest forecast of CO_2 concentration over the lifetime of concrete member, or based on the average of the aforementioned forecasts. Yoon et al. (Yoon et al., 2007) has proposed Eq. (5) for adjustment of carbonation depth for changes in CO_2 concentration.

$$X_c = \sqrt{\frac{2D_{CO2}(t)}{a} k\ C_{CO2}(t) \cdot t \left(\frac{t_0}{t}\right)^{n_m}} \tag{5}$$

To correct the errors of the previous models, Stewart et al. (2011) have proposed the following equation for adjustment of carbonation depth for changes in CO_2 concentration over the lifetime of concrete structure:

$$X_c = \sqrt{\frac{2f(t)D_{CO2}(t)}{a} k \int_0^t C_{CO2}(t)dt \left(\frac{1}{t}\right)^{n_m}} \tag{6}$$

All the parameters of Eqs. (5) and (6) are similar to those in Eq. (1), except *f*(*t*) which is used to allow the formula to account for the effect of temperature on diffusion coefficient and thus on carbonation depth (Bastidas-Arteaga et al., 2013). *f*(*t*) can be obtained from Eq. (7), which is based on the Arrhenius equation (Lindvall, 1998; FIB, 2006; Wang et al., 2012; Shayanfar et al., 2015a).

$$f(t) = e^{\frac{E}{R}\left(\frac{1}{293} - \frac{1}{273 + T_{av}(t)}\right)} \tag{7}$$

$$T_{av} = \frac{\sum_{t_0}^{t} T(t)}{t - t_0} \tag{8}$$

In Eqs. (7) and (8), *f*(*t*) represents temperature at time *t*, *E* is the activation energy of the corrosion process (E = 40) (Yoon et al., 2007), and R is the gas constant (R = 8.314 × 10^{-3}) (Bastidas-Arteaga et al., 2013).

Table 2 presents the mean, coefficient of variation, and probability distribution function of probabilistic parameters required for calculations.

Table 2. Required Statistical Values

Variable	Units	Mean	COV	Distribution	Reference
$D_{c,ref}$	m^2/s	3×10^{11}	0.20	Log-normal	Engelund et al. (2000)
C_{th}	Wt.%cem.	0.50	0.20	Normal	Yoon et al. (2007)
c_t	mm	30	0.25	Normal	Val and Trapper (2008)
c_q	J/kg°c	1,000	0.10	Beta on [840; 1170]	Val and Trapper (2008)
ρ_c	kg/m^3	2,400	0.04	Normal	Engelund et al. (2000)
f_c	MPa	40	0.15	Normal	Vu and Stewart (2000)
f_y	MPa	600	0.10	Normal	Neville (1981)

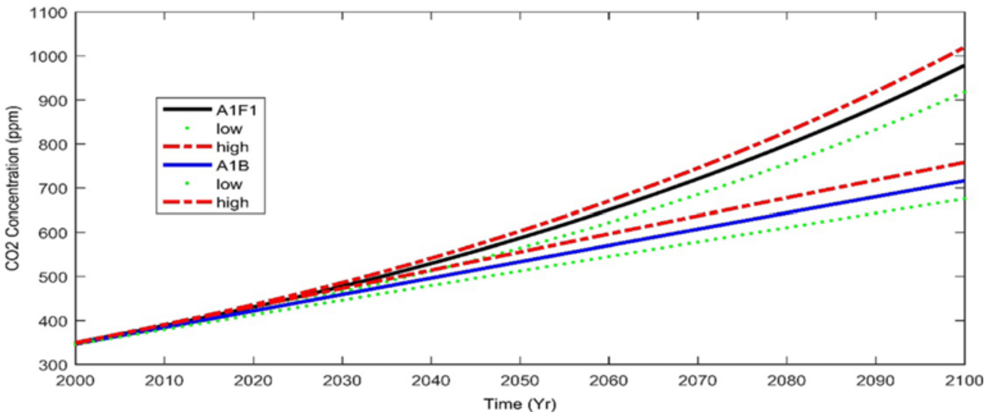


Fig. 1. CO_2 Concentration Forecasts for a 100-Year Period

Finally, assuming C as the concrete cover depth and $X_c(t)$ as the carbonation depth at time t, the limit state is defined.

The limit state corresponds to the borderline of desirable and undesirable performance at $G(t) = 0$. When $G(t) > 0$, corrosion has not started yet, and otherwise it is already underway.

In the present study, research objectives were pursued through using the Monte Carlo simulation with one million samples. To calculate the probability of corrosion, the number of samples in which $G(t) < 0$ was divided by the total number of samples (Shayanfar et al., 2016b). It should be noted that the modeling was performed in MATLAB.

3. CO_2 Concentration Variations

CO_2 concentration growth is very difficult to model as it depends on the forecasts of population growth, economic condition, and the use of clean technologies among many other factors (Bastidas-Arteaga et al., 2013). Fig. 1 shows two CO_2 concentration forecasts recommended by IPCC in 1990 (Val and Trapper, 2008). In this diagram, CO_2 concentration has been predicted based on two different assumptions regarding the Earth's future. In the A1F1 state, it is assumed that strong economic development and high population growth will continue until the mid-21st century and the use of fossil fuels will continue as before. In contrast, the A1B state assumes that by that time, the common sources of energy will be clean. In other words, A1F1 gives a pessimistic prediction of CO_2 concentration in the future while A1B gives an optimistic one. One can use either of the curves plotted in Fig. 1 to calculate the probability of corrosion over an extended period of time.

4. Results and Discussion

Determinants of carbonation or concrete durability can be classified into three main groups: 1) external factors or environmental conditions, 2) concrete's internal or structural factors, and 3) construction and operation conditions (Ramezanianpour, 1992).

4.1 Effect of Environmental Factors

In section 2, we described three formulas, namely Eqs. (1), (5) and (6), for calculation of carbonation depth. In Eq. (1), CO_2 concentration is assumed to be constant, and the impact of its variations on the carbonation depth is neglected; while in Eq. (5) proposed by Yoon and Eq. (6) suggested by Stewart, this effect is considered. It was also observed that CO_2 concentration may change as pessimistically predicted in A1F1 or as optimistically predicted in A1B, depending on the future conditions. Fig. 2 compares the results of Eqs. (5) and (6) for the change in CO_2 concentration. These results are for a concrete member made with cement content of 370 kg/m^3 and water-cement ratio of 0.45 ($n_d = 0.2$, $D_1 = 0.22$), and is located in an unprotected environment ($n_m = 0$). It is also assumed that there will be zero change in the ground temperature, and CO_2 concentrations will change as predicted in A1F1.

As it can be seen, the carbonation depth given by Yoon's formula is always greater than the output of Stewart's formulation. This seems a logical difference, since to calculate the carbonation depth of a specified period, Yoon's formula uses the last CO_2 concentration of that period as the reference. For example, to calculate the carbonation depth of a structure fifty years after its construction, Yoon's formula uses the CO_2 concentration predicted for the 50th year, which is very conservative given that CO_2 concentration gradually moves toward that concentration. Therefore, this formula can be expected to result in overestimation. However, in the method proposed by Stewart et al., to calculate the carbonation depth of a specified period, CO_2 concentration predictions will be integrated with respect to the time. In other words, in this method, carbonation depth estimated for the end of a period depends on the CO_2 concentrations predicted for every single year of that period.

As it is evident from the above, the formula proposed by Stewart et al. has the most perfect formulation among the existing methods and can be expected to give realistic estimations of carbonation effects.

4.2 Effect of Concrete's Structural Factors

4.2.1 Water-Cement Ratio

The most important structural factors affecting the carbonation

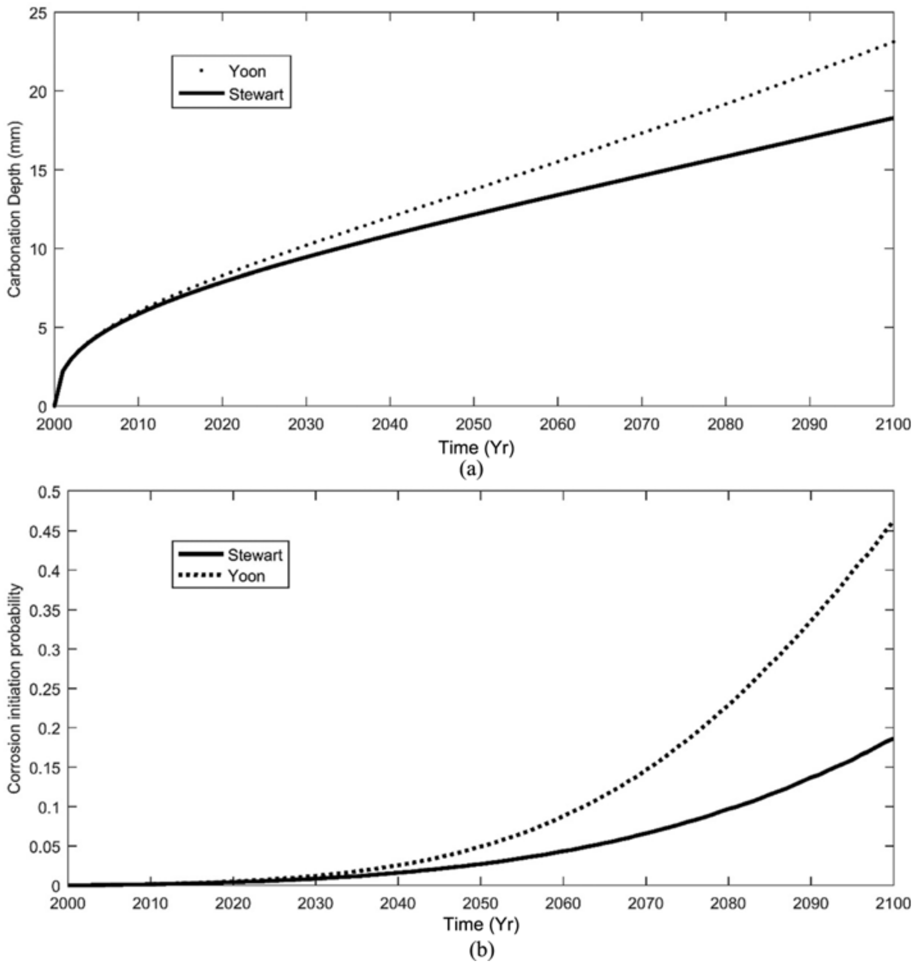


Fig. 2. Outputs of the Formulas Proposed by Yoon and Stewart: (a) Carbonation Depth, (b) Corrosion Probability

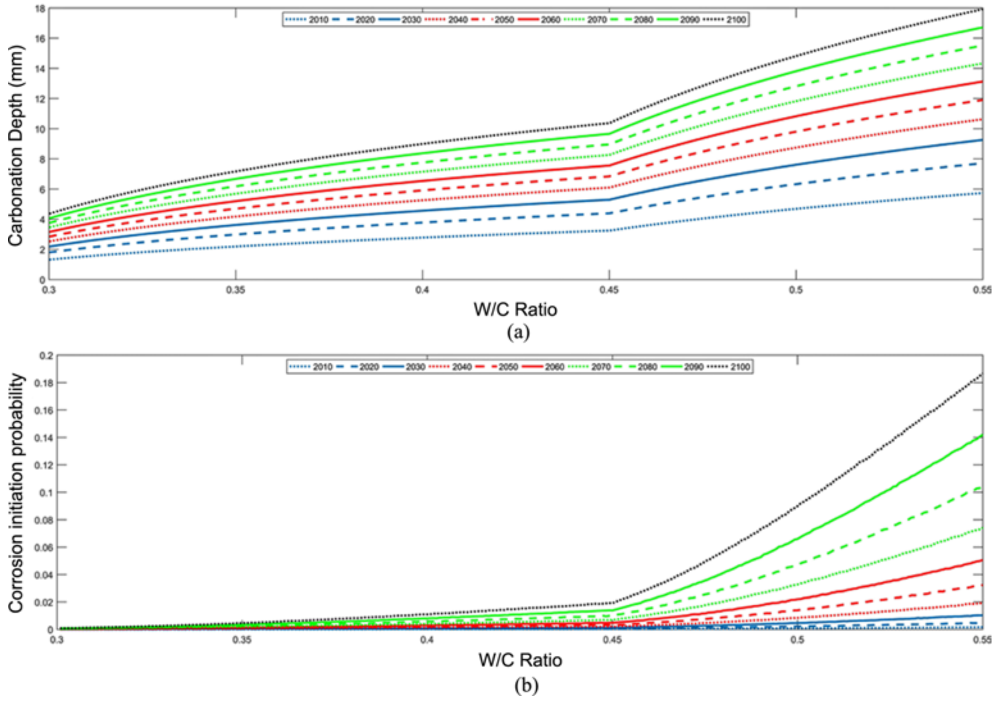


Fig. 3. Effect of Water-Cement Ratio on Carbonation Depth and Corrosion Initiation Probability: (a) Effect of Water-Cement Ratio on Carbonation Depth, (b) Effect of Water-Cement Ratio on Corrosion Initiation Probability

Table 3. Carbonation Depth and Corrosion Probability for Different Water-Cement Ratios

W/C	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
0.30	C.D[1] = 2.87 mm	3.48	3.87	4.16	5.03	5.24	5.87	6.43	6.94	7.19
	C.I.P[2] = 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.35	C.D = 3.03 mm	3.87	4.04	4.58	5.24	5.97	6.53	7.09	7.69	7.95
	C.I.P = 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.40	C.D = 3.17 mm	4.07	4.63	5.94	6.34	6.93	7.74	7.98	8.33	8.47
	C.I.P = 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
0.45	C.D = 3.28 mm	4.43	5.35	6.15	6.9	7.63	8.34	9.04	9.75	10.47
	C.I.P = 0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.03
0.5	C.D = 4.71 mm	6.35	7.65	8.79	9.85	10.87	11.87	12.87	13.87	14.88
	C.I.P = 0.00	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.09	0.11
0.55	C.D = 5.74 mm	7.71	9.26	10.63	11.91	13.13	14.33	15.52	16.72	17.93
	C.I.P = 0.00	0.01	0.02	0.03	0.05	0.07	0.10	0.12	0.17	0.19

[1] Carbonation Depth
[2] Corrosion Initiation Probability

depth and ultimately the concrete durability are the concrete's cement content and water-cement ratio. This section discusses the effect of these factors on the durability of concrete structures.

One of the key structural factors affecting the durability of concrete is its water-cement ratio. As previously noted, the parameters n_d and D_1 used in calculation of CO_2 diffusion coefficient and eventually the carbonation depth depend on water-cement ratio.The values of n_d and D_1 for three different water-cement ratios are provided in Table 1. According to this Table, the values of these coefficients for water-cement ratios of 0.30 to 0.55 can be obtained by linear interpolation.

In Fig. 3, corrosion initiation probability given by Stewart's formula is plotted against water-cement ratio. It should be noted that each of these curves represents the variations in the probability of corrosion initiation in a particular year for different water-cement ratios. As can be seen, 10 curves has been obtained for the years 2010, 2020, 2030, ... , and 2100. Obviously, since both carbonation depth and chance of corrosion increase with time, the highest curve, which represents the highest likelihood of corrosion, belongs to the year 2100, and the lowest curve (lowest probability of corrosion) pertains to the year 2010.

According to these results, as water-cement ratio increases, concrete permeability and in turn, carbonation depth and corrosion probability increase and, as a results, concrete durability decreases. As it can be observed, the increase in the probability of corrosion may reach up to 40% by 2100. Table 3 shows the carbonation depth and corrosion probability at different years for six different water-cement ratios. As it is evident, for water-cement ratios of less than 0.6, corrosion probability in 2060 is less than 10%. It should be noted that the Monte Carlo simulation is not suitable for determination of very small probability values (Shayanfar et al., 2016b), but in the present study, the calculated probability values are large enough to assure that Monte Carlo simulation is reliable.

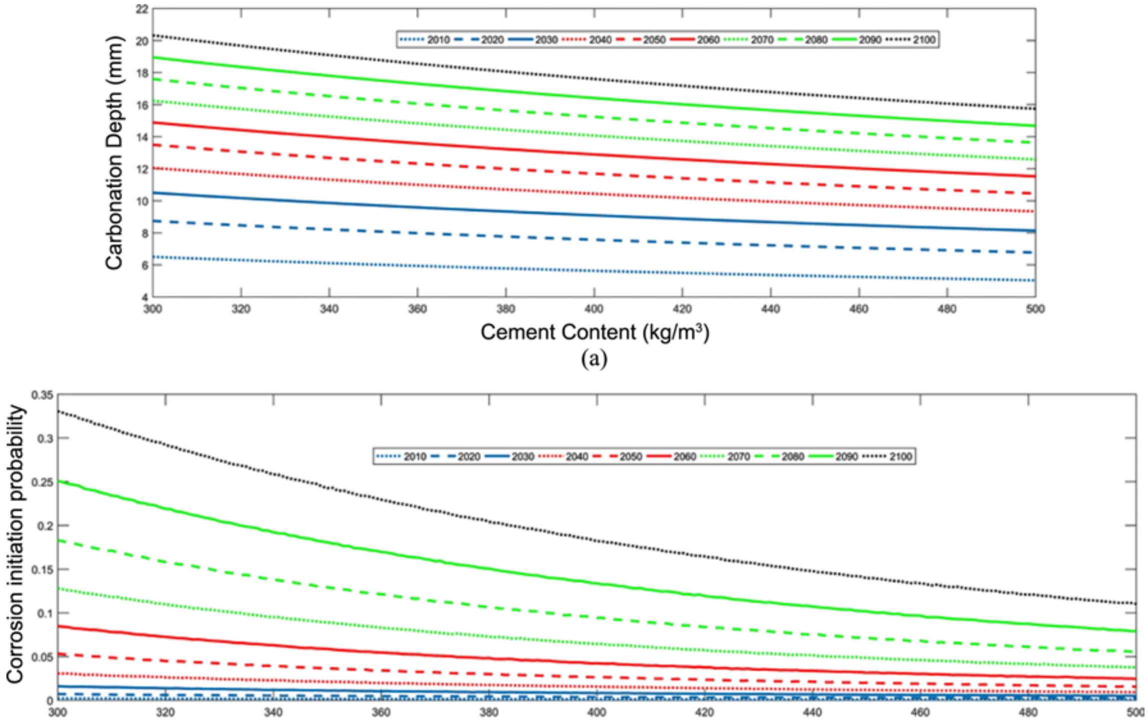
With water-cement ratios of less than 0.5, corrosion probability over the 100 year period remains less than 10%. This probability remains less than 22% for water-cement ratios of less than 0.55. As pointed out by (Bastidas-Arteaga et al., 2013), in the low-water to cement ratios, the rate of CO_2 penetration into the concrete member is lower; in this regard, to calculate the coefficients D_1 and n_d, the linear interpolation was performed. The growth rate of these two parameters was considered in the range of 0.3 – 0.45 less than the range of 0.45 to 0.55; in other words, two different interpolations was performed for the two mentioned intervals, which eventually led to the fracture of the graph in Fig. 3.

4.2.2 Cement Content

Another determinant of durability of a RC structure is the concrete's cement content. As seen in Eq. (3), concrete's cement content affects the carbonation depth through the coefficient *a*. To investigate the effect of this factor on carbonation, the probability of corrosion in different years was obtained for different cement contents with water-cement ratio fixed at 0.55. The results are plotted in Fig. 4. These results are also based on Stewart's method as well as the assumptions that CO_2 concentration will change as predicted in A1F1, there will be zero change in ground temperature, and the member will be located in an unprotected environment.

In Fig. 4, the probability of corrosion initiation at different years is plotted against the water-cement ratios based on which they were obtained. Again, each of the 10 curves in Fig. 4 represents the variations in the probability of corrosion initiation by a particular year (2010, 2020, 2030, ... , and 2100) for different cement contents.

According to the results presented in Fig. 4 and Table 4, for a fixed water-cement ratio, as the concrete's cement content increases, both carbonation depth and corrosion probability decrease. In explanation of this result, it can be argued that the increase in mix design's cement content decreases the porosity of the resulting concrete member, which makes it more resistant to CO_2 diffusion, leading to lower depth of carbonation. In addition, the increase in cement content increases the alkalinity of concrete matrix, causing a slower rate of carbonation.



(a)

(b)

Fig. 4. Effect of Cement Content on Carbonation Depth and Corrosion Initiation Probability: (a) Effect of Cement Content on Carbonation Depth, (b) Effect of Cement Content on Corrosion Initiation Probability

Table 4. Carbonation Depth and Corrosion Probability for Different Cement Content

C_e (kg/m^3)	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
300	C.D = 6.49 mm	8.75	10.5	12.06	13.5	14.69	16.25	17.6	18.96	20.33
	C.I.P = 0.00	0.00	0.01	0.03	0.05	0.08	0.12	0.18	0.25	0.33
340	C.D = 6.12 mm	8.25	9.90	11.32	12.68	13.99	15.26	16.51	17.83	19.07
	C.I.P = 0.00	0.00	0.01	0.02	0.04	0.06	0.10	0.14	0.19	0.25
380	C.D = 5.78 mm	7.80	9.36	10.72	12.01	13.23	14.42	15.64	16.84	18.09
	C.I.P = 0.00	0.00	0.01	0.02	0.03	0.05	0.07	0.11	0.15	0.20
420	C.D = 5.50 mm	7.40	8.89	10.02	11.42	12.57	13.73	14.87	16.02	17.16
	C.I.P = 0.00	0.00	0.00	0.01	0.02	0.04	0.06	0.08	0.12	0.16
460	C.D = 5.25 mm	7.06	8.50	9.75	10.9	12.01	13.12	14.19	15.29	16.43
	C.I.P = 0.00	0.00	0.00	0.01	0.01	0.03	0.05	0.07	0.10	0.13
500	C.D = 5.04 mm	6.77	8.14	9.34	10.46	11.53	12.59	13.63	14.68	15.75
	C.I.P = 0.00	0.00	0.00	0.00	0.01	0 .02	0.04	0.05	0.08	0.11

Moreover, as shown in Table 4, the maximum depth of carbonation and the highest probability of corrosion during the 100-year period are 20.33 mm and 33% respectively and pertain to cement content of 300 kg/m^3 (with w/c = 0.55). But with the same water-cement ratio (w/c = 0.55), using a cement content of 500 kg/m^3 will decrease the maximum carbonation depth and corrosion probability to 15.75 mm and 11%, respectively. In other words, these results show that, with water-to-cement ratio fixed at 0.55, the cement content can be adjusted so that corrosion probability will reduce by two thirds (from 33% to 11%).

4.3 Effect of Construction and Operation Conditions

Concrete cover depth and surface protection state are among the most determinants of carbonation depth and durability of concrete members. This section discusses the effect of these factors on the durability of concrete structures.

4.3.1 Cover Depth

Concrete cover depth has a significant influence on the durability of concrete member. As can be expected, an increase in concrete cover depth will result in higher durability of concrete member. In Fig. 5, the probability of corrosion initiation by different years

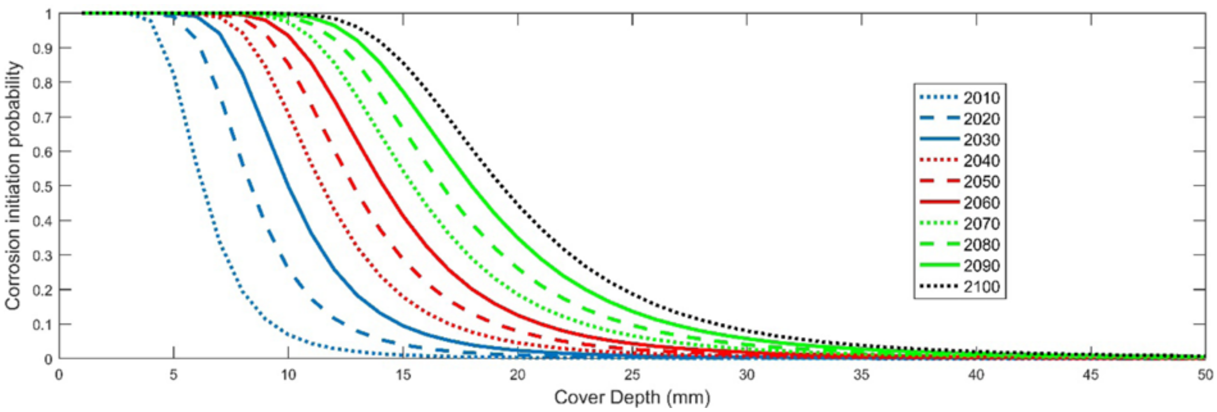


Fig. 5. Effect of Concrete Cover Depth on the Probability of Corrosion Initiation

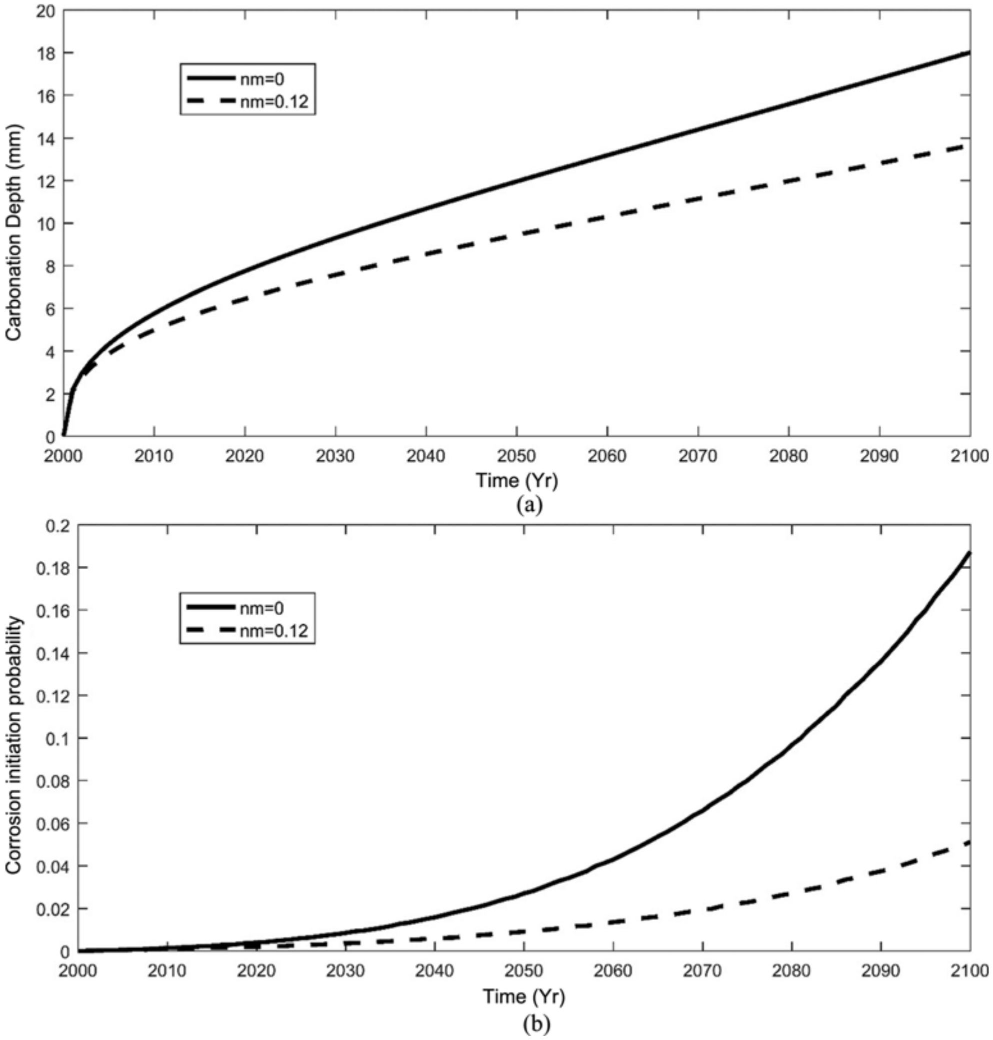


Fig. 6. Effect of Surface Protection on Concrete Durability: (a) Effect of Surface Protection on Carbonation Depth, (b) Effect of Surface Protection on Corrosion Initiation Probability

is plotted against the cover depth. The mean, coefficient of variation, and distribution of relevant statistical variables can be found in Table 2. Again, all calculations are based on the assumptions that CO_2 concentration will change as predicted in A1F1, there will be zero change in ground temperature over the 100-year period, water-cement ratio is 0.55, the cement content is 370 kg/m^3, and $n_m = 0$.

As shown in Fig. 5, with the increase in effective cover depth (actual cover depth - 25 mm) from 0 to 50 mm, the probability of corrosion decreases. In some cases, a 10 mm increase in the cover depth leads to 35% reduction in the probability of corrosion by the year 2100. Overall, it can be concluded that for a concrete member with water-cement ratio of 0.55 and the cement content of 370 kg/m^3, the use of an effective cover depth of 35 mm will reduce the probability of corrosion over the 100-year period to less than 10%.

4.3.2 Coating and Surface Protection

Another factor associated with the durability of concrete is the level of surface protection (coating). A layer of coating can increase the durability of concrete member by protecting its surface against direct exposure to environmental elements. In other words, a protective layer such as finishing material that is applied on RC member inhibits the CO_2 diffusion into concrete, thus increasing its durability.

As noted above, surface protection can be provided by finishing and facade materials, or alternatively, by positioning of a member in a place away from the direct exposure to environmental elements. For example, an RC column that is positioned in the interior of a building is not directly exposed to CO_2 diffusion. To put it differently, the extent of surface protection (n_m) depends on all the factors that prevent a direct contact between CO_2 and concrete member.

Considering the above-mentioned, concrete surface protection can be provided at different levels and may vary with the member function and position. In the description of Eq. (1), we discussed the concrete age factor n_m that allows the formula to account for the changes in the member's surrounding environment. Some sources recommend that this factor should be set to zero for unprotected members and 0.12 for protected members (Bastidas-Arteaga et al., 2013), but other sources suggest that it should be less than 0.3 without specifying an exact value (Stewart et al., 2002).

In any case, we first determined the carbonation depth and corrosion initiation probability over the next 100 years for $n_m = 0$ and $n_m = 0.12$ (Fig. 6), and then estimated these parameters for the n_m values of between 0 and 0.5 (Fig. 7).

Also as shown in Fig. 6, carbonation depth of the year 2100 is approximately 2 mm (10%) less when $n_m = 0.12$ than when $n_m = 0$, and this corresponds to 12% less corrosion initiation probability in that year. Moreover, as it can be seen in Table 5, even a minimal surface protection ($n_m = 0.05$) will reduce the risk of corrosion over the next 100 years to less than 11%. Accordingly, exposed concrete members are recommended to be covered with finishing and facade material in order to provide a surface protection against corrosive elements and improve the durability of the structure.

As it is observed from the available models for evaluating the durability of concrete structures, many factors affect the durability of these structures. In one hand, due to the importance of durability against CO_2 ingress in some structures, it is necessary to specify clear criteria for assessing the durability of structures and to consider the design of concrete mix design and on the other hand, there are so few studies on the design of structures for durability. As a proposal, structures based on durability can be categorized as follows (Table 6). It should be noted that the

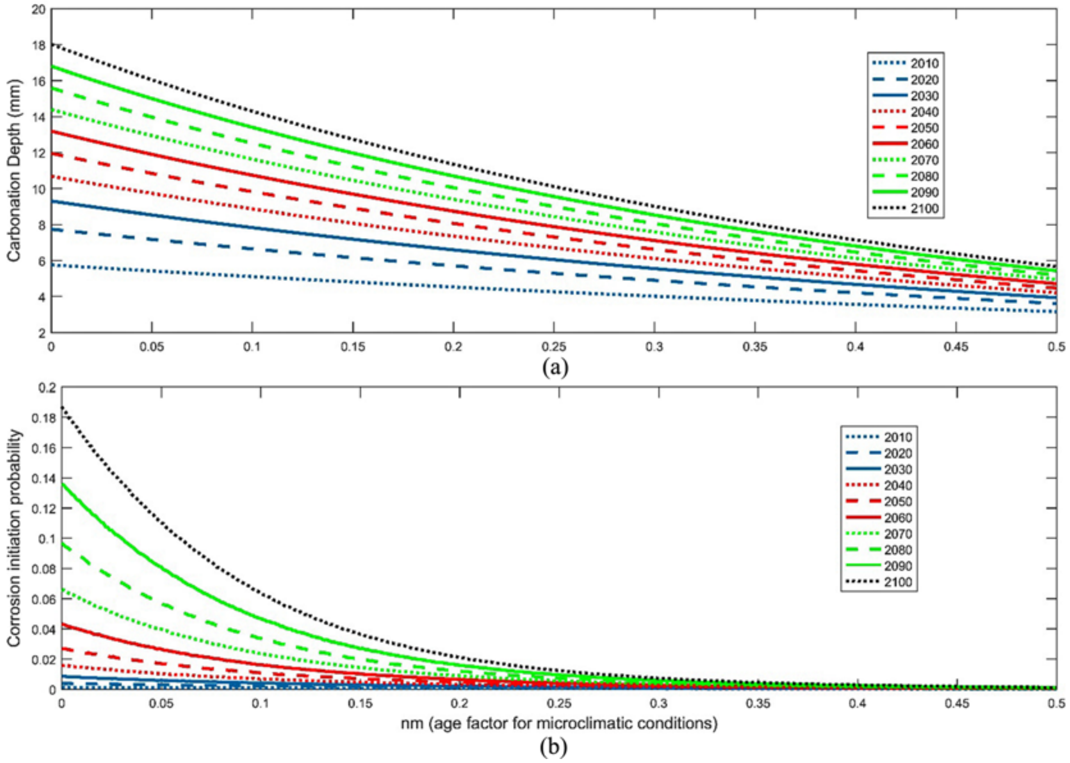


Fig. 7. Effect of Surface Protection on Concrete Durability: (a) Effect of Surface Protection on Carbonation Depth, (b) Effect of Surface Protection on Corrosion Initiation Probability

Table 5. Carbonation Depth and Corrosion Initiation Probability for Different Surface Protection Conditions

n_m	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
0	C.D = 5.76 mm	7.75	9.30	12.06	10.68	14.69	14.4	15.6	16.8	18.02
	C.I.P = 0.00	0.00	0.00	0.01	0.02	0.04	0.06	0.09	0.13	0.18
0.05	C.D = 5.43 mm	7.18	8.53	9.69	10.78	11.93	12.95	13.97	14.98	16.03
	C.I.P = 0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.05	0.08	0.11
0.10	C.D = 5.13 mm	6.70	7.86	8.86	9.94	10.81	11.70	12.54	13.45	14.23
	C.I.P = 0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.05	0.06
0.15	C.D = 4.80 mm	6.13	7.20	8.10	8.90	9.58	10.38	11.01	11.80	12.75
	C.I.P = 0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.03
0.20	C.D = 4.54 mm	5.70	6.56	7.31	8.02	8.65	9.29	9.97	10.78	11.42
	C.I.P = 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02
0.25	C.D = 4.26 mm	5.28	6.04	6.76	7.27	7.80	8.30	9.02	9.56	10.01
	C.I.P = 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01

Table 6. Classification of Concrete Structures Based on Durability

Structure	Criterion	w/c	Concrete	Surface Protection (n_m)
HDS[1]	The probability of failure during the 100 year period is less than 10%	w/c < 0.5	Ce ≥ 500	$n_m > 0.05$
MDS[2]	The probability of failure during the 100 year period is more than 10%	w/c > 0.5	Ce < 500	$0 < n_m \leq 0.05$

[1] High Durable Structure

[2] Moderate Durable Structure

effective depth of the cover above stirrups is assumed to be 35 mm. In Table 6, it was tried to classify concrete members based on durability through using three parameters of water-to-cement ratio, cement content and surface protection. However, it is noteworthy that due to the complexity of the proposed models for the durability of concrete structures and the variety of factors affecting the durability of concrete members, the proposed classification is an initial proposal and needs to be further elucidated in subsequent studies.

5. Conclusions

There are several methods for estimating the carbonation depth over a given time period andsome of these methods utilize a constant (time invariant) CO_2 concentration for their estimations. We observed that among the existing methods, the results given by Stewart's formulation are more realistic.

It was found that using a higher water-cement ratio results in easier CO_2 diffusion into concrete and, consequently, accelerated corrosion of RC member. The results also showed that for a fixed water-cement ratio, the use of a greater cement content in mix design leads to improved concrete durability. Besides, the findings illustrated that an increase in mix design's cement content from 300 to 500 kg/m^3 will reduce the carbonation depth and probability of corrosion initiation by 100th year from 20.33 mm and 33% to 15.75 mm and 11%, respectively.

Our assessment of the effect of construction and operation factors on the durability of concrete showed that using a thicker concrete cover will improve the durability of RC member. It was also observed that members that are not directly exposed to CO_2 in the environment are less likely to experience carbonation-induced corrosion. The results showed that increasing the effective cover depth to 35 mm will result in the reduction in the probability of corrosion initiation over the next 100 years to less than 10%. For a specific mix design, the carbonation depth and corrosion initiation probability estimated for 100 year of operation without surface protection ($n_m = 0$) were 18.02 mm and 18% respectively, but the assumption of a minimal surface protection ($n_m = 0.05$) decreased these estimates to 16.03 mm and 11%, whereas the assumption of proper surface protection ($n_m = 0.15$) could decrease these estimate even further to 12.75 mm and 3%, respectively.

After analyzing the results of this study, the criteria of the structures were classified into two categories of high durable and moderate durable structures, and numerical values for the identification of high durability structures were presented. Finally, it is suggested that, by conducting further research and considering all the factors affecting the durability of concrete, the classification given for structures based on durability be completed.

Acknowledgements

Not Applicable

ORCID

Not Applicable

References

Ababneh AN, Benboudjema F, Xi Y (2003) Chloride penetration in unsaturated concrete. *Journal of Materials in Civil Engineering* 15(2):183-191, DOI: 10.1061/(ASCE)0899-1561(2003)15:2(183)

Akiyama M, Frangopol DM, Yoshida I (2010) Time-dependent reliability analysis of existing RC structures in a marine environment using hazard associated with airborne chlorides. *Engineering Structures* 32(11):3768-3779, DOI: 10.1016/j.engstruct.2010.08.021

Basheer L, Kroop J, Cleland DJ (2001) Assessment of durability of concrete from its permeation properties: A review. *Construction and Building Materials* 15:93-103, DOI: 10.1016/S0950-0618(00)00058-1

Bastidas-Arteaga E, Bressolette PH, Chateauneuf A, Sánchez-Silva M (2009) Probabilistic lifetime assessment of RC structures under coupled corrosion-fatigue processes. *Structural Safety* 31(1):84-96, DOI: 10.1016/j.strusafe.2008.04.001

Bastidas-Arteaga E, Chateauneuf A, Sánchez-Silva M, Bressolette P, Schoefs F (2010) Influence of weather and global warming in chloride ingress into concrete: A stochastic approach. *Structural Safety* 32(4):238-249, DOI: 10.1016/j.strusafe.2010.03.002

Bastidas-Arteaga E, Schoefs F, Stewart MG, Wang X (2013) Influence of global warming on durability of corroding RC structures: A probabilistic approach. *Engineering Structures* 51:259-266, DOI: 10.1016/j.engstruct.2013.01.006

Bjarnadottir S, Li Y, Stewart MG (2011) A probabilistic-based framework for impact and adaptation assessment of climate change on hurricane damage risks and costs. *Structural Safety* 33(3):173-185, DOI: 10.1016/j.strusafe.2011.02.003

Engelund S, Mohr L, Edvardsen C (2000) General guidelines for durability design and redesign: DuraCrete, probabilistic performance based durability design of concrete structure, CUR, Lyngby, Denmark

FIB (2006) Model code for service life design. The International Federation for Structural Concrete, Lausanne, Switzerland, DOI: 10.35789/fib.BULL.0034

Ghanooni-Bagha M, Shayanfar MA, Farnia SMH (2018) Cracking effects on chloride diffusion and corrosion initiation in RC structures via finite element simulation. *Scientia Iranica* 21(3), DOI: 10.24200/sci.2018.50496.1725

Ghanooni-Bagha M, Shayanfar MA, Shirzadi-Javid AA, Ziaadiny H (2016) Corrosion-induced reduction in compressive strength of self-compacting concretes containing mineral admixtures. *Construction and Building Materials* 113(1):221-228, DOI: 10.1016/j.conbuildmat.2016.03.046

Ghanooni-Bagha M, Zarei S, Savoj HR, Shayanfar MA (2019) Time-dependent seismic performance assessment of corroded reinforced concrete frames. *Periodica Polytechnica Civil Engineering* 63(2):631-640, DOI: 10.3311/PPci.12653

Gjørv OE, Vennesland, El-Busaidy AHS (1977) Electrical resistivity of concrete in the oceans. Offshore Technology Conference, Houston, TX, USA, DOI: 10.4043/2803-MS

IPCC (2007) Climate change 2007: The physical science basis. Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, New York, NY, USA

Kaveh A, Massoudi MS, Ghanooni-Bagha M (2014) Structural reliability analysis using charged system search algorithm. *Iranian Journal of Science and Technology* 38(2):439-448, DOI: 10.22099/IJSTC.2014.2420

Lindvall A (1998) Duracrete – Probabilistic performance based durability design of concrete structures, 2nd International PhD Symposium in civil engineering, Budapest, Hungary

Neville AM (1981) Properties of concrete, 3rd edition. Longman Scientific and Technical, Harlow, UK

Østvik JM (2005) Thermal aspects of corrosion of steel in concrete. PhD Thesis, The Norwegian University of Science and Technology, Trondheim, Norway

Poupard O, L'Hostis V, Catinaud S, Petre-Lazar I (2006) Corrosion damage diagnosis of a reinforced concrete beam after 40 years natural exposure in marine environment. *Cement and Concrete Research* 36(3):504-520, DOI: 10.1016/j.cemconres.2005.11.004

Ramezanianpour AA (1992) Recommendations and suggestions for the stability of concrete on the coasts and southern islands of the country. Road, Housing and Urban Development Research Center, Tehran, Iran

Saetta A, Scotta R, Vitaliani R (1993) Analysis of chloride diffusion into partially saturated concrete. *ACI Mater* 90(5):441-451

Shamsad A (2003) Reinforcement corrosion in concrete structures, its monitoring and service life prediction a review. *Cement and Concrete Composites* 25(4-5):459-471, DOI: 10.1016/S0958-9465(02)00086-0

Shayanfar MA, Barkhordari MA, Ghanooni-Bagha M (2015a) Probability calculation of rebars corrosion in reinforced concrete using css algorithms. *Journal of Central South University* 22(8):3141-3150, DOI: 10.1007/s11771-015-2851-9

Shayanfar MA, Barkhordari MA, Ghanooni-Bagha M (2015b) Estimation of corrosion occurrence in RC structure using reliability based PSO optimization. *Periodica Polytechnica Civil Engineering* 59(4)531-543, DOI: 10.3311/PPci.7588

Shayanfar MA, Barkhordari MA, Ghanoonibagha M (2016a) Effect of longitudinal rebar corrosion on the compressive strength reduction of concrete in reinforced concrete structure. *Advances in Structural Engineering* 19(6):897-907, DOI: 10.1177/1369433216630367

Shayanfar MA, Ghanooni-Bagha M, Jahani E (2016b) Reliability theory of structures, 1st edition. IUST Publication, Tehran, Iran

Stewart MG, Rosowsky DV (1998) Structural safety and serviceability of concrete bridges subject to corrosion. *Structural Engineering* 4(4):146-155, DOI: 10.1061/(ASCE)1076-0342(1998)4:4(146)

Stewart MG, Teply B, Kralova H (2002) The effect of temporal and spatial variability of ambient carbon dioxide concentrations on carbonation of RC structures. 9th international conference on durability of building materials and components, March 17-20, Brisbane, Australia

Stewart MG, Wang X, Nguyen MN (2011) Climate change impact and risks of concrete infrastructure deterioration. *Engineering Structure* 33(4):1326-1337, DOI: 10.1016/j.engstruct.2011.01.010

Stewart MG, Wang X, Nguyen MN (2012) Climate change adaptation for corrosion control of concrete infrastructure. *Structural Safety* 35(1):29-39, DOI: 10.1016/j.strusafe.2011.10.002

Sudret B, Defaux G, Pendola M (2007) Stochastic evaluation of the damage length in RC beams submitted to corrosion of reinforcing steel. *Civil Engineering and Environmental Systems* 24(2):165-178, DOI: 10.1080/10286600601159305

Talukdar S, Banthia N, Grace JR, Cohen S (2012) Carbonation in concrete infrastructure in the context of global climate change: Part 2 - Canadian urban simulations. *Cement and Concrete Composite* 34(8):931-935, DOI: 10.1016/j.cemconcomp.2012.04.012

Tuutti K (1982) Corrosion of steel in concrete. Swedish Cement and Concrete Institute, CBI, Stockholm, Sweden

Val DV, Stewart MG, Melchers RE (1998) Effect of reinforcement corrosion on reliability of highway bridges. *Engineering Structure* 20:1010-1019, DOI: 10.1016/S0141-0296(97)00197-1

Val DV, Trapper PA (2008) Probabilistic evaluation of initiation time of chloride-induced corrosion. *Reliability Engineering and System Safety* 93(3):364-372, DOI: 10.1016/j.ress.2006.12.010

Vu KAT, Stewart MG (2000) Structural reliability of concrete bridges including improved chloride-induced corrosion models. *Structural Safety* 22(4):313-333, DOI: 10.1016/S0167-4730(00)00018-7

Wang X, Stewart M, Nguyen M (2012) Impact of climate change on corrosion and damage to concrete infrastructure in Australia. *Climate Change* 110:941-957, DOI: 10.1007/s10584-011-0124-7

Yoon IS, Çopuroğlu O, Park KB (2007) Effect of global climatic change on carbonation progress of concrete. *Atmospheric Environment* 41(34):7274-7285, DOI: 10.1016/j.atmosenv.2007.05.028

Yoon C, Kim JG, Kwang L (2006) Corrosion behavior of steel bar embedded in fly ash concrete. *Corrosion Science* 48:1733-1745, DOI: 10.1016/j.corsci.2005.05.019