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Effect of Different Factors on the Service Life of Concrete Structures in Chloride Environment: A Parametric Study - Part Two

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Abstract*— *In this paper, the effect of different factors on the service life of reinforced concrete structures in marine environments is investigated through a parametric study. The considered case for the study was the two-dimensional diffusion problem. By solving the selected model for corrosion initiation by Finite Element Method, it has been concluded that, corrosion initiates at corner bars before side bars. Also, concrete elements subjected to two-dimensional diffusion are more susceptible to corrosion initiation than elements subjected to one-dimensional diffusion. Moreover, increase in water to cement ratio by 12.5%-50% in range 0.20-0.40 reduces the service life by 6.2%-31%, and by 5.3%-16.9% for the range 0.40-0.60. And, the increase in concrete cover in the range of 20-40 mm by 12.5% - 50% increases the service life by 5.1%-18.8%, and in the range of 35-60 mm by 2.9%-10.3%. The addition of fly ash and blast-furnace slag increased the service life by 6.35%-69.7% due to increase of age factor by 25%-200%. Furthermore, the addition of silica fume by 5%-15% increases the service life by 21.7%-81.2%. Regarding the environmental factors, increasing of temperature by 25%-75% reduces service life by 4.7%-12.75%, and reducing of relative humidity by 25%-50% increases the life by 17.5%-90.4%.are also given.

Keywords*— *Concrete; Corrosion; Chloride diffusion; Service life; Numerical; Finite Element Method; Two-dimensional diffusion.

I. INTRODUCTION

This paper is the extension of the research work, performed by the authors in [1], which deals with the influence of various factors on the service life of reinforced concrete structures serving in chloride-borne climates and subjected to one-dimensional diffusion. In this second part of the study, a parametric study is performed to investigate the effect of water to cement ratio, concrete cover, mineral admixtures addition, temperature, and relative humidity on the corrosion initiation time in case of two-dimensional diffusion problem to represent multi-surface exposed elements.The study is based on a selected model for corrosion initiation prediction. The model is based on Fick´s second law. In its basic form, the fundamental one-dimensional partial differential equation for chloride diffusion through concrete structures can be written as [17]:

$$\frac{\partial C(x,t)}{\partial t} = D\,\frac{\partial^2 C(x,t)}{\partial x^2} \qquad (1)$$

where *C(x,t)* is the chloride ion concentration at a distance *x* from the chloride-exposed concrete surface after being exposed for a period of time *t* to chloride concentration at surface, and *D* is the chloride diffusion coefficient. However, to account for the two-dimensional diffusion process, Eq. (1) can be extended to a more general equation as follows:

$$\frac{\partial C(x,y,t)}{\partial t} = D_{mod.}\left[\frac{\partial^2 C(x,y,t)}{\partial x^2} + \frac{\partial^2 C(x,y,t)}{\partial y^2}\right] \qquad (2)$$

where *C(x,y,t)* is the chloride ion concentration at point *(x,y)* in the element domain at time *t*.

The model is solved numerically by the finite element method using COMSOL MULTIPHYSICS software [31].Full description of the factors included in the model is given in [1] and briefly stated in Table 1.

Table.1: Model factors and associated notations.

$D(t) = D_{ref}.(\frac{t_{ref}}{t})^m$	[7, 19, 20]
$D_{ref} = 10^{(-12.06+2.40*w/c)}*e^{-0.165*\%SF}$	[21]
$m = 0.2 + 0.4(\%FA/50 + \%SG/70) \leq 0.6$	[21]
$F(T) = \exp\left[\frac{U_c}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right]$	[15]
$\text{F(RH)} = \left[1 + \frac{(1-\text{RH})^4}{(1-\text{RHc})^4}\right]^{-1}$	[24]
$D_{mod.} = D_{ref} * f(T) * f(RH) * \left(\frac{t_{ref}}{t}\right)^m$	
$Cs = C_0 + k\sqrt{t}$	[30]

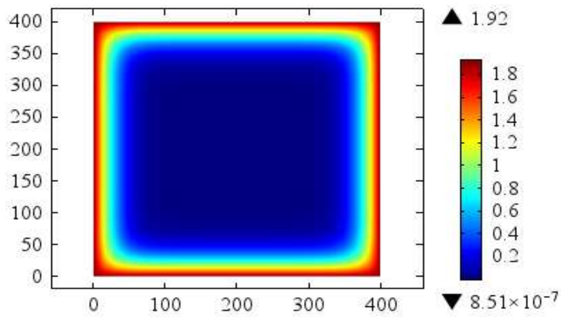
Notations	
D(t)	Diffusion coefficient at time *t*
D_{ref}	Reference diffusion coefficient at time t_{ref}(usually 28 days)
m	Age factor
w/c	Water to cement ratio

% FA	Amount of fly ash (≤50%)
% SG	Amount of slag (≤70%)
% SF	Amount of silica fume
U_c	Activation energy of chloride diffusion (35 kj/mol),
R	Universal gas constant (8.314 J/mol K),
T_{ref}	Reference temperature (20°C =293.15 K)
T	Ambient temperature.
RH	Ambient relative humidity
RH_c	Reference relative humidity (0.75)
Cs	Surface chloride concentration
C_0	Initial build-up of surface chloride
k	A constant under a linear build-up condition

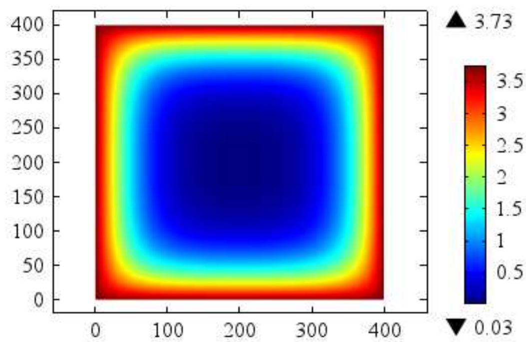
II. PARAMETRIC STUDY FOR TWO-DIMENSIONAL DIFFUSION

2.1 Reference Case

To perform the study, a reference case is assumedfor the factors based on code recommendations to ensure durability requirements in chloride environment [32-34]. A square column of side width 400 mm is modeled using concrete cover of 40 mm, and water to cement ratio of 0.40. The reference diffusion D_{28}=7.9433E-12 m^2/s. Assuming that no mineral admixtures are used, the age factor *m* is 0.20. The average temperature and relative humidity are assumed to be 20°C and 100% respectively. The surface chloride is assumed to apply to all boundaries with a value of 0.6537 + 0.3217*tas in [1]. Under these conditions, the chloride concentration within the element expressed as a contour graph is shown in Fig. 15 at 5, 25, 50, and 100 years, respectively.



(a)



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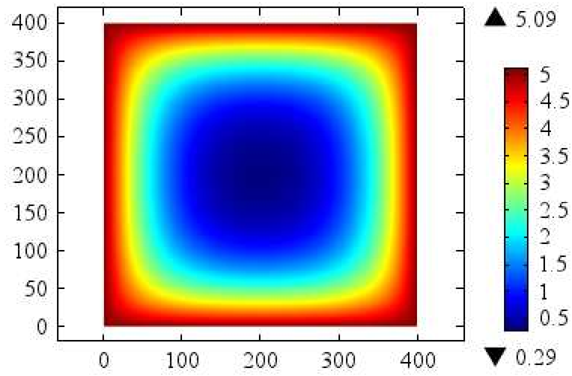

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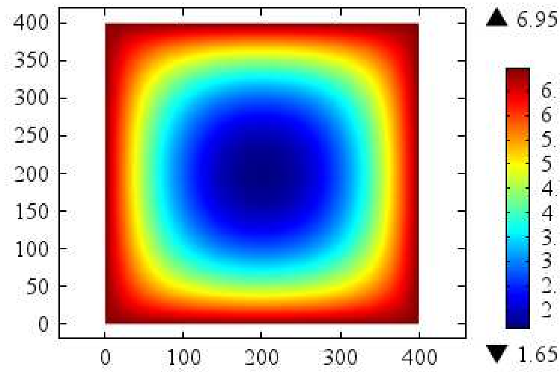

(d)

Fig.1:Chloride concentration contours at (a) 5, (b) 25, (c) 50, and (d) 100 years.

Fig. 2 shows the concentration variation along a line section drawn between point (0, 40) and point (400, 40) at different times. Noting that 40 mm is the reference cover. It is shown that corner points are exposed to the highest concentration when compared with edge points. Thus, reinforcement bars located at the corner are more susceptible to corrosion initiation than edge bars. So, this study is performed considering concentration accumulation at a point in the domain representing the corner bar which is (cover, cover). The chloride concentration variation with time at point (40, 40) is shown in Fig. 3.

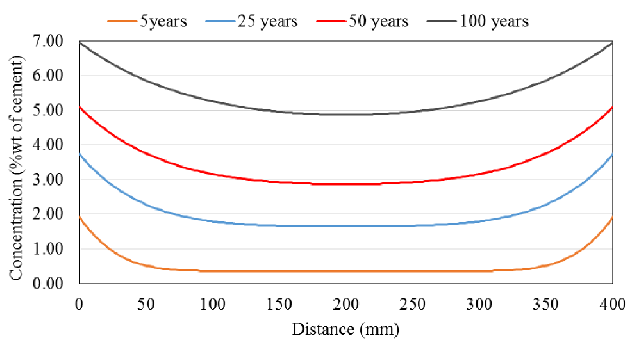

Fig. 2: Concentration variation along a line section drawn between point (0, 40) and point (400, 40) at different times.

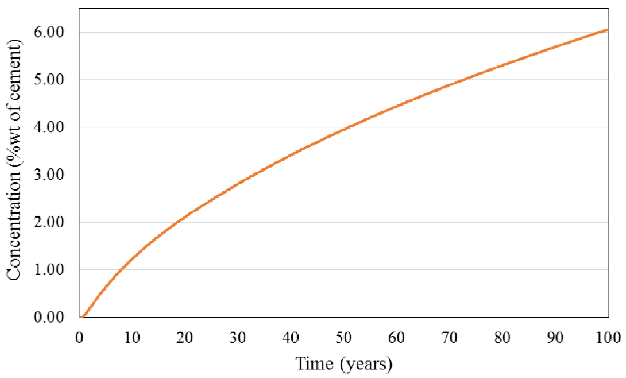

Fig. 3:Variation of chloride concentration with time at point (40, 40).

To study a parameter, its value is changed while the others remain constant, and the results are then compared with the reference case to quantify its effect. Noting that service life is used to refer to corrosion initiation. As codes recommendations imply that service life is 50 years, the comparison is performed at this age. And, the change in concentration due to change in a parameter value is considered to express the change in service life.

2.2 Water to cement ratio (w/c) effect

The value of water to cement ratio is changed from 0.20 to 0.60 with a step of 0.05. The effect of *w/c* on the time variation of chloride concentration at point (40, 40) mm is shown in Fig. 4.

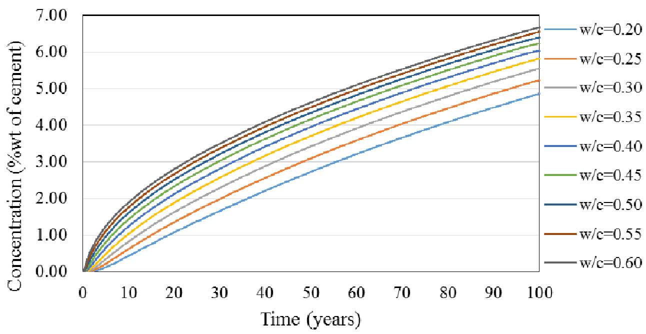

Fig. 4:Variation of chloride concentration with time at point (40, 40) for different values of w/c ratio.

The behavior is almost the same as that of one dimensional diffusion except that the values of concentration are higher. This confirms that the two dimensional effect cause earlier corrosion initiation. The percentage of change in concentration*C* with respect to the reference concentration C_{ref}corresponding to *w/c* of 0.40 is shown in Fig. 5.

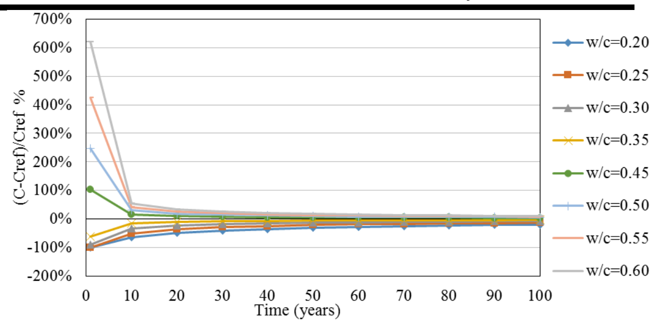

Fig.5:Change percentage of chloride concentration at (40, 40) for different values of w/c ratio with time.

At 50 years, the reduction of *w/c*by12.5%, 25%, 50% results in a reduction of concentration by 6.2%, 13.5%, and 31%, respectively, comparable with one-dimensional results. The reduction ratios of service life due to increase of*w/c* by the same ratios are 5.31%, 9.8% and 16.9%. These values are smaller than reduction ratios, and also those of one dimensional results, because here in two dimensional diffusion, the effect of *w/c* is more obvious in range of 0.20 to 0.40than 0.40 to 0.60.

2.3 Concrete cover (cov) effect

Keeping all the reference values as constants and changing the value of concrete cover from 20 to 60 mm with a step of 5 mm, the time variation of chloride concentration at point (cover, cover) for each cover value is plotted in Fig. 6. The rate of percentage change in chloride concentration *C* with respect to the concentration of reference cover 40 mmC_{ref} is illustrated in Fig. 7. At 50 years, the reduction of concrete cover by 12.5%,30%, and 50% results in an increase of concentration by 5.14%, 10.11%, and 18.8% respectively, and the increase of concrete cover by the same percentages results in a reduction of concentration by 5.36%, 10.7%, and 21.35% respectively.

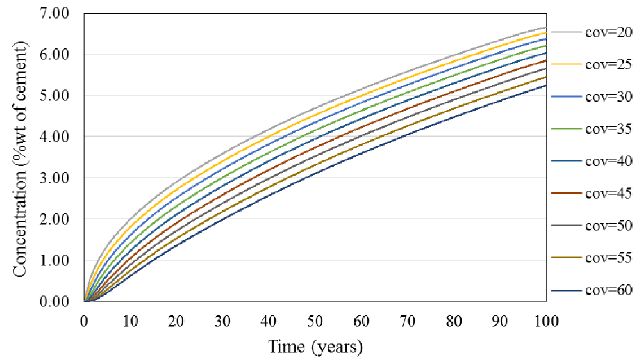

Fig.6:Variation of chloride concentration with time at (cover, cover) for each cover value.

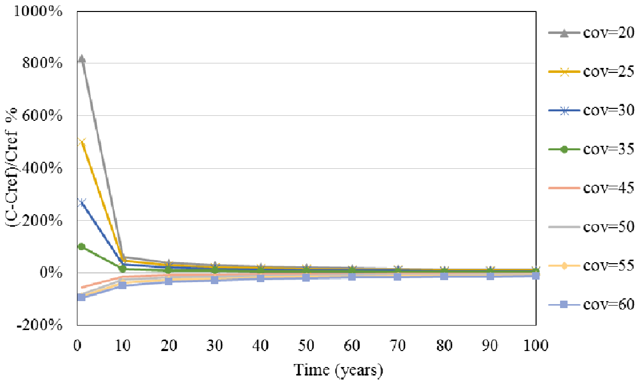

Fig.7:Change percentage of chloride concentration at (cover, cover) mm for each value of concrete cover with time.

2.4 Age factor (m) effect

The value of *m* is changed from 0.20 to 0.60 with a step of 0.05. Figure8indicates the time variation of chloride concentration at (40, 40) for different values of *m*, andthereduction of chloride concentration *C*with respected to that of the reference value $C_{ref}$is depicted in Fig. 9.Values of concentration reduction (or service life increase) due to an increase of age factor by 25%, 50%, 75%, 100%, 125%, 150%, 175%, and 200%at 50 years are 6.35%, 13.7%, 21.9%, 31%, 40.7%, 50.7%, 60.5%, and 69.8% respectively.

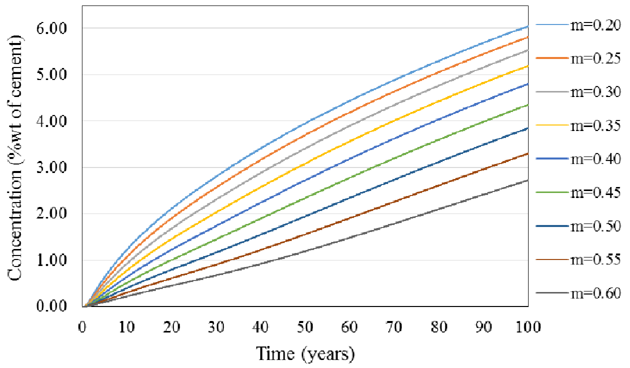

Fig.8:Variation of chloride concentration with at (40, 40) for different values of age factor.

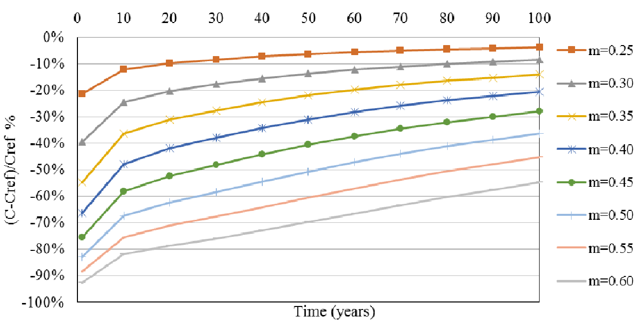

Fig.9:Reduction percentage of chloride concentration at (40, 40) mm for each value of age factor with time.

2.5 Effect of silica fume(SF) addition

The percentage of silica fume is used as 5%, 10%, and 15%. The corresponding values of D_{28} are 3.48E-12, 1.53E-12, and 6.68E-13 m^2/s. The time variation of chloride concentration at (40, 40) is illustrated for each percentage of silica fume along with the reference value 0% in Fig. 10.

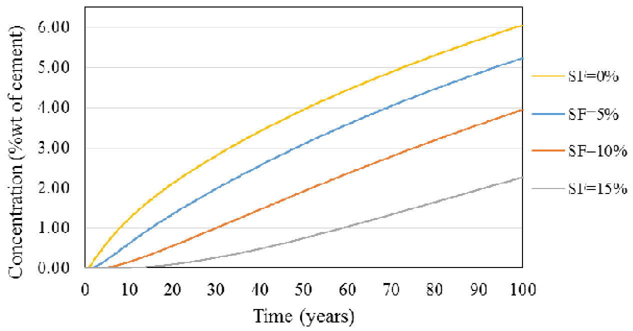

Fig.10:Variation of chloride concentration with time at (40, 40) mm each value of silica fume.

The percentage decrease of chloride concentration for different values of the silica fume with respect to that of the reference value is shown in Fig. 11. At 50 years, the addition of 5%, 10%, or 15% of silica fume results in a reduction of concentration by about 21.7%, 51.5%, and 81.15% respectively.

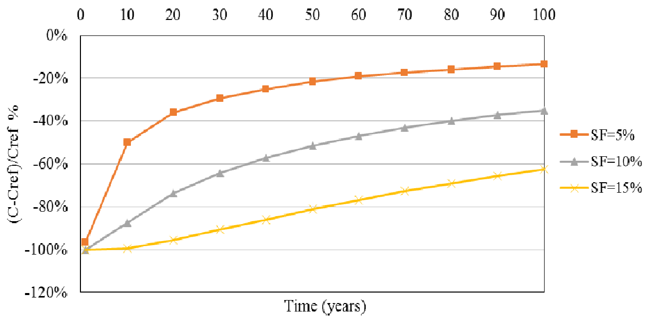

Fig.11:Reduction percentage of chloride concentration at (40, 40) for each value of silica fume with time.

2.6 Effect of ambient temperature (T)

Fig. 12 shows the variation of chloride concentration with time at (40, 40) for different values of ambient temperature: 25°C, 30°C, and 35°C, respectively.

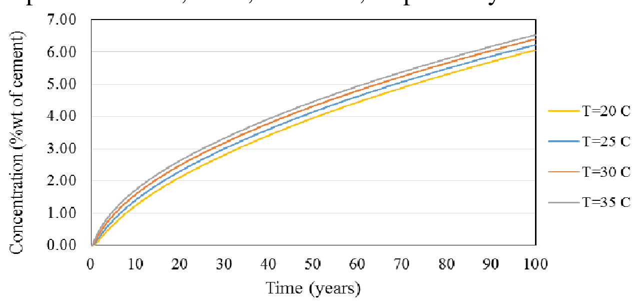

Fig.12:Variation of chloride concentration with time at (40, 40) for different values of ambient temperature.

The rate of chloride concentrations change relative to the reference value at ambient temperature, 20°C at for different ambient temperature values is shown in Fig. 13. At 50 years, temperature increase by 25%, 50, and 75% increases the concentration 4.7%, 9.25% and 12.75%, respectively.

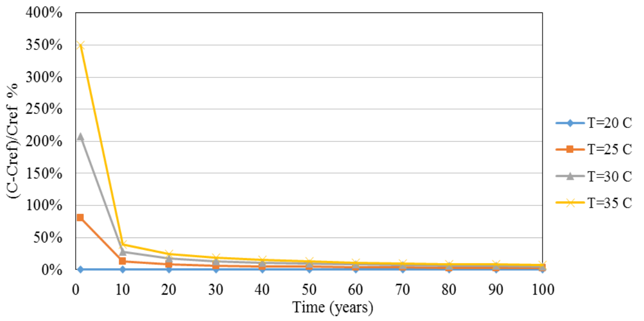

Fig. 13: Increase percentage of chloride concentration at (40, 40) for different values of ambient temperature with time.

2.7 Effect of relative humidity (RH)

The RH values is ranged from 50% to 75% with a step of 5%. The concentration distributions plotted against time at (40, 40) for each RH along with the reference value of 100% are shown in Fig. 14.

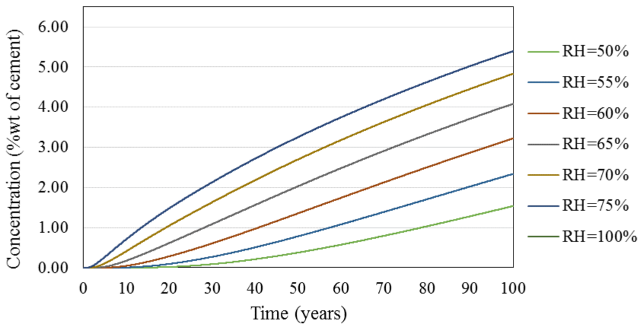

Fig.14: Variation of chloride concentration with time at (40, 40) for different values of relative humidity

The change of chloride concentration at (40, 40) with respect to the reference concentration at different times is illustrated in Fig. 15 for different values of RH. The ratios of reduction in concentration corresponding to reduction of 25%, 30%, 35%, 40%, 45%, or 50% at 50 years are 17.5%, 31.6%, 48.5%, 65.6%, 81.1%, 90.4%. It is obvious that RH has a significant effect on the chloride ingress, and it should not be overlooked when predicting the service life at a certain location.

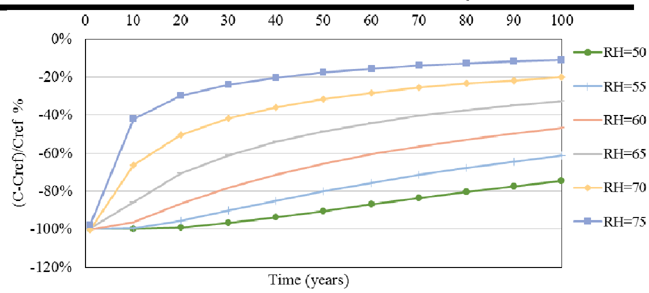

Fig.15: Reduction percentage of chloride concentration at (40, 40) for each RH value with time

Now it is important to mention that the obtained ratios for service life reduction or increase due to change in a certain parameter are based on a conservative approach as the comparison is performed only at 50 years based on the assumption that the intended service life is 50 years, but if the actual life is less or more than 50 years, these change ratios will increase or decrease as shown in figures for change percentages. Thus, it is a conservative approach to quantify the effect of different parameters on service life.

III. CONCLUSIONS

Based on the previous results, the following points are concluded:

1- Corrosion initiates at corner bars before edge bars. Also, concrete elements subjected to two dimensional diffusion are more susceptible to corrosion initiation than elements subjected to one dimensional diffusion.
2- In the range 0.20-0.40 of *w/c*, the change (increase/decrease) of *w/c* by 12.5%-50% changes (decrease/increase) the service life of the structure by 6.2%-31%, and by 5.3%-16.9% in range of 0.40-0.60.
3- The variation in concrete cover in the range of 20-40 mm by 12.5% - 50% changes the service life by 5.1%-18.8%, and in the range of 35-60 mm by 2.9%-10.3%.
4- The increase of age factor*m* by 25% - 200% increases the service life by 6.35%-69.7%, and the addition of silica fume by 5% - 15% increases the service life by 21.7%-81.2%.
5- Increase of temperature by 25%-75% reduces service life by 4.7%-12.75%, and reduction of relative humidity by 25%-50% increases the life by 17.5%-90.4%.

REFERENCES

[1] Sakr M, El-Mahdy O, El-Dash K. Effect of different factors on the service life of concrete structures in chloride environments: a parametric study – part

one. International Journal of Advanced Engineering Research and Science 2016; 3: 40-48.

[2] COMSOL MULTIPHYSICS, user guide (www.comsol.com).

[3] Crank, J.: The mathematics of diffusion. Second edition. Clarendon Press. Oxford, UK, 1986.

[4] DuraCrete, General guidelines for durability design and redesign. The European Union- Brite EuRam III, Project no. BE95-1347/R15, Probabilistic Performance based Durability Design of Concrete Structures, 2000.

[5] Magnat P, Molly B. Predicting of long term chloride concentration in concrete. Mater Struct 1994; 27:338–46.

[6] Maage M, Helland S, Carlsen J. Chloride penetration in high performance concrete exposed to marine environment. Proc of RILEM international Workshop on Durability of High Performance Concrete, 1994; 194-207.

[7] Thomas M, Bentz E. Computer program for predicting the service life and life-cycle costs of reinforced concrete exposed to chlorides. Life365 Manual, 2001.

[8] Yuan Q, Shi C, De Schutter G, Audenaert K. Effect of temperature on transport of chloride ions in concrete. In M. G. Alexander et al. (Eds.), Concrete repair, rehabilitation and retrofitting II, 2009: 345-51.

[9] Saetta A, ScottaR, Vitaliani R. Analysis of chloride diffusion into partially saturated concrete. ACI Mater J 1993; 90(5): 441–51.

[10] Ann K, Ahn J, Ryou J. The importance of chloride content at the concrete surface in assessing the time to corrosion of steel in concrete structures. Constr Build Mater 2009; 23: 239–45.

[11] ECP 203. Design and construction of concrete structures. Egypt, 2007.

[12] BS 8110. Structural use of concrete, Part 1. Code of practice for design and construction. United Kingdom, 1997.

[13] ENV 206. Concrete Performance, production, placing and compliance criteria, European Pre-standard, 1992.