Effect of Different Factors on the Service Life of Concrete Structures in Chloride Environments: A Parametric Study – Part One

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Abstract— *This paper presents a comprehensive parametric study to determine the effect of different factors on the service life of reinforced concrete structures in chloride-laden environment. A model for corrosion initiation is selected and solved numerically by Finite Element Method for one-dimensional diffusion problem. It has been found that increase in water to cement ratio by 12.5%-50% in range of 0.20-0.40reduces the service life by 8%-35%, and by 7.35%-30.5% for the range 0.40-0.60. Also, the increase in concrete cover in the range of 20-35 mm by 14%-42%increases the service life by 8.1%-25.8%, and in the range of 35-60 mm by 7.7%-21.8%.Regarding mineral admixtures, the addition of fly ash and blast-furnace slag resulted in enhances the service life by 8%-70.7% due to increase of age factor by 25%-200%. Moreover,the addition of silica fume by 5%-15% increases the service life by 25.5%-80.6%.Finally, the rise of temperature by 25%-75% reduces the service life by 6.45%-18.7%, and the reduction of relative humidity by 25%-50% increases the life by 21.2%-89%. These values are based on a conservative approach and tend to guide the practice engineer on how these parameters affect service life of concrete structures.*

Keywords—Concrete, Corrosion, Chloride diffusion, Service life, Numerical, Finite Element Method, One-dimensional diffusion.

I. INTRODUCTION

Reinforced concrete is the most frequently used material in construction over the world due to its versatility and availability of constituents. Structures can be exposed to severe exposure conditions during their service life resulting in deterioration of concrete.In chloride laden environments such as marine exposure, chloride-induced corrosion is the major deterioration mechanismof reinforced concrete structures [1]. Corrosion adversely affect the structural behavior of the corroded element, and may cause premature failure of structures. It causes reduction of flexural stiffness, shear capacity of the element, and loss of bond strength [2-4].Moreover, rust produced as a result of corrosion expands to cause volume increase at the steel/concrete interface. Volume expansion develops tensile stresses in concrete, which ultimately results in cracking of concrete along the rebar length and eventual spalling of the concrete cover [5]. The U.S. Federal Highway Administration (FHWA) and NACE International initiated a 2-year study in 1999 entitled “Corrosion Costs and Preventive Strategies in the United States” on the direct costs associated with metallic corrosion in nearly every U.S. industry sector. Results of the study show that the total annual estimated direct cost of corrosion in the U.S. is a staggering $276 billion [6].

Hence, increasing attention was given in the past decadesto develop models to predict initiation time for chloride-induced corrosion[7, 8]. These models help to evaluate the performance of structures and develop optimized and cost-saving corrosion control strategies.Corrosion initiates when chloride ions accumulate on the reinforcement surface with a concentration exceeds a certain threshold value [9]. Chloride ions may transport through concrete by different mechanisms: diffusion, adsorption, migration, and wick action. Diffusion due to concentration gradient is considered to be the dominant mechanism [10].Fick’s second law is widely used to mathematically represent the diffusion process whose analytical solutionbased on assuming a constant boundary condition and diffusion coefficient is as given in Eq. (1) [11]:

$$C(x,t) = C_i + (C_S - C_i).\left[1 - \operatorname{erf}\left(\frac{x}{2\sqrt{D.t}}\right)\right] \qquad (1)$$

where C_i is the initial chloride concentration in concrete form mix materials and it is considered as the initial condition to the diffusion problem, C_s is the chloride concentration at the surface and the boundary condition to the problem, D is the chloride diffusion coefficient of concrete, erf is the mathematical error function, and $C(x,t)$ is the chloride concentration at distance x apart from thechloride-exposed surface at time t. Diffusion coefficient is the key element that represent the resistance of concrete to chloride ion ingress. Several factorsaffect the diffusivity of chlorides and consequently the service life. Page et al. [12] found that the diffusion increases as water to cement ratio increases. Thomas and Bamforth

[13], and Song et al. [14] indicated that addition of fly ash, blast-furnace slag and silica fume reduced the diffusion ofchlorides due to a refined pore structure. Yuan et al. [15] found that higher temperatures result in higher diffusion coefficient. Relative humidity is found to influence the diffusion process [16]. Also, Eq. (1) implies that increasing the concrete cover will delay the corrosion initiation time.

In this research work, a parametric study is performed to investigate the effect of previously mentioned factors on the corrosion initiation time, and try to quantify how the change in one factor changes the service life. The study is based on a selected model for corrosion initiation prediction. The research work is organized into two parts to be published in two papers. In this first paper, the model is solved numerically be the finite element method considering one-dimensional diffusion problem to represent one-surface exposed elements, while in the second part, results of two-dimensional diffusion problem would be given. This study also tends to provide the practice engineer with a guide on how these factors influence the service life of reinforced concrete structures.

II. SELECTED MODEL FOR CHLORIDE TRANSPORT

The selected model for corrosion initiation is based on Fick´s second law. Adjustments are made in the diffusion equation to allow for the time dependency of the surface chloride, and the diffusion coefficient. The effect of environmental variables is also considered. The fundamental one-dimensional partial differential equation for chloride diffusion through concrete structures can be written as [17]:

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

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.

2.1 Time Dependency Of Diffusion Coefficient

It was realized that the diffusion coefficient is not constant but decreases with time as refinement of pore structure continues due to progression of the hydration process [18].Thetime dependency of chloride diffusion coefficient is considered as follows [7, 19,20]:

$$D(t) = D_{ref}.\left(\frac{t_{ref}}{t}\right)^m \quad (4)$$

where$D(t)$ is the diffusion coefficient at time t, $D_{ref}$is the reference diffusion coefficient at time t_{ref}(usually 28 days), and m is an age factor that defines the reduction of diffusion coefficient with time. This relation is valid until the hydration process is complete and no further pore refinement takes place, assumed 25 years. Beyond this point the value of diffusion coefficient remains constant at the 25 years value [21].

Based on a large database of bulk diffusion tests, a software package (Life-365) uses the following relations to express the reference diffusion coefficient, and age factor [21]:

$$D_{ref} = 10^{(-12.06+2.40*w/c)}\ (\mathrm{m}^2/\mathrm{s}); \quad (5a)$$

$$m = 0.2 + 0.4(\%FA/50 + \%SG/70) \le 0.6 \quad (5b)$$

wherew/c is the water to cement ratio, and *% FA* and *% SG* are the amount of fly ash (≤50%) and slag (≤70%), respectively.The equation for age factor m considers only the addition of fly ash and slag. Silica fume is assumed to have no effect on the age factor, but affects the reference diffusion by a multiplied factor*F(SF)* equals$e^{-0.165*\%SF}$, where*% SF* is the amount of silica fume [21].

2.2 Temperature and Relative Humidity Effect on Diffusion Coefficient

Temperature and relative humidity are considered the main environmental variables that affect the chloride ingress into concrete [22, 23].Yuan et al. [15] conducted an experimental study to examine the effect that temperature had on the diffusion coefficient. They found that increasing the temperature results in increasing the diffusion coefficient. The trend of the chloride profiles did not change with increasing temperature, but the penetration depth increased.In this model, the effect of temperature was taken into account by multiplying the reference diffusion coefficient by a factor *F(T)* obtained from Arrhenius law [15, 24]:

$$F(T) = \exp\left[\frac{U_c}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (6)$$

where *Uc* is the activation energy of chloride diffusion in concrete, reported as 23, 39.9 kJ/mol for water to cement ratio 0.35, and 0.6 respectively [15], assumed to be 35 kJ/mol in this study,*R* is the universal gas constant (8.314 J/mol K), Tref is the reference temperature (20°C =293.15 K), and *T* is the ambient temperature.The effect of relative humidity was taken into account by multiplying the reference diffusion coefficient by a factor *F(RH)*[24]:

$$\mathrm{F(RH)} = \left[1 + \frac{(1-\mathrm{RH})^4}{(1-\mathrm{RHc})^4}\right]^{-1} \quad (7)$$

Where *RH* is the ambient relative humidity, and RH_c is the reference relative humidity (assumed 75% [25])

2.3 ModifiedChloride Diffusion Coefficient

The modified value of chloride diffusion coefficient in concrete considering the time dependency, and the effect of temperature and relative humidity is:

$$D_{mod.} = D_{ref} * f(T) * f(RH) * \left(\frac{t_{ref}}{t}\right)^{m},$$

or$$D_{mod.}(t, T, RH) = D_{ref} * \exp\left[\frac{U_c}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] * \left[1 + \frac{(1-RH)^4}{(1-RHc)^4}\right]^{-1} * \left(\frac{t_{ref}}{t}\right)^{m} \quad (8)$$

where $D_{ref}$is the reference diffusion coefficient (m^2/s), U_c is the activation energy of chloride diffusion in concrete (35000 J/mol), R is the universal gas constant (8.314 J/mol K),T_{ref} is the reference temperature (293.15 K),T is the ambient temperature (K),RH is the ambient relative humidity, RH_c is the reference relative humidity (0.75), t_{ref} is the reference age of concrete (28 days), t is the age of exposure (days), and m is the age factor.

2.4 Time Dependency of Surface Chloride Concentration

Surface chloride concentrationCs is a very important parameter in service life prediction models. It represents the severity of the surrounding environment, and the boundary condition of the diffusion problem.Adopting appropriate values for Cs is important to predict adequately the future chloride penetration [26].Experimental work [27-30] showed that the chloride ions on the concrete surface exposed to a marine environment can be accumulated then to increase with time.The time dependency of Cs is considered throughan equation related totime. Ann et al. [30] studied and compared previously suggested relations: constantCs, linear build-upwith time t ($Cs = kt$; where k is a constant under a linear build-up condition), square root build-up ($Cs = k\sqrt{t}$; where k is a constant under a square root build-up condition). They indicated that the constant surface chloride model produced the greatest level of chloride penetration, as an initial set of surface chloride content was overestimated indicating a greater risk of chloride-induced corrosion, whereas the linear and square root build-up models indicated 2–3 times longer duration of initiation time. Finally, they suggested a more realistic relation for surface chloride build-up ($Cs = C_0 + k\sqrt{t}$; where C_0 is the initial build-up of surface chloride, k is a constant under a linear build-up condition) to account for the existence of chloride ions at concrete surface at early age of exposure.In this model, the proposed surface chloride build-up is adopted, but the constant k is used as a constant under a square root build-up condition.

2.5 MathematicalImplementation

Finite element analysis method is used to solve the diffusion problem and the set of equations forming the model by using “Transport of Diluted Species” module in COMSOL MULTIPHYSICS software [31]. This module provides a predefined modeling environment for studying the transport of chemical species by diffusion or other mechanism using Fick’s law based on the assumption that all species present are dilute; that is, that their concentration is small compared to a solvent fluid or solid.

III. PARAMETRIC STUDY

In this section, the effect of each factor on the chloride penetration and service life isinvestigated. A reference case is assumedfor these factors based on code recommendations to ensure durability requirements in chloride environment [32-34]. The value of one factor is changed while the others remain constant, andthe results are then compared with the reference case to quantify the effect of each parameter.Noting that service life is divided to corrosion initiation and propagation phases [8], in this study the term “service life” will be used to refer to corrosion initiation. Codes recommendations imply that service life is 50 years so the comparison is performed at this age (a conservative approach as indicated next). The change in concentration due to change in a parameter value is considered to express the change in service life.

For the present study, the surface chloride value is assumed based on the experimental study performed by Costa and Appleton [27] for elements exposed to air-borne chlorides carried by the sea wind. These results are shown in Table 1.

Table.1: Values of Cs at different times for the atmospheric exposure [27].

Time (years)	1	1.25	1.5	2	2.5	3	3.5	4
C_s (% wt of cement)	0.85	0.93	1.39	1.32	1.39	1.78	1.63	1.94

No data is available on the value of Csat initial exposure. It is approximately obtained by carrying out simple linear regression on these data. The resulting equation for Cs is 0.6537 + 0.3217*t, and correlation factor R^2 is 0.85. The value of Cs at initial age is 0.6537 along with the experimental results is used to perform another regression to relate Cs and $\sqrt{t}$ (see Fig. 1). The intercept $C_0$is 0.454 and the slope (k) is 0.656. It is important to mention that this assumed value of Cs will not affect the parametric study as it will be kept constant for all cases of study.

3.1 One-Dimensional Diffusion

3.1.1 Reference Case

In this part, one dimensional slab element is modeled using an average value of the minimum specified value of concrete cover in codes, 35 mm, and maximum water to cement w/c ratio of 0.40. According to this value of w/c ratio the reference diffusion D_{28} is 7.94E-12 m^2/s. The initial chloride concentration is assumed to be zero. No cement replacement materials are used thus, the age factor *m* is 0.20. The annual average temperature *T* is 20^{o}C, and the annual average relative humidity *RH* is 100%. Based on these conditions, the chloride concentration variation with depth from the surface at 5, 25, 50, and 100 years is shown in Fig. 2.

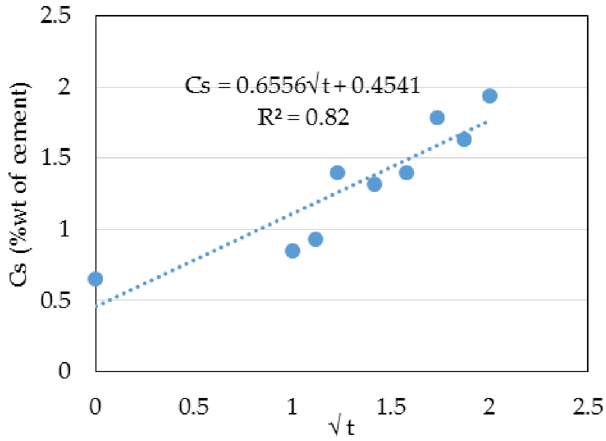

Fig.1: Assumed surface chloride concentration obtained by linear regression.

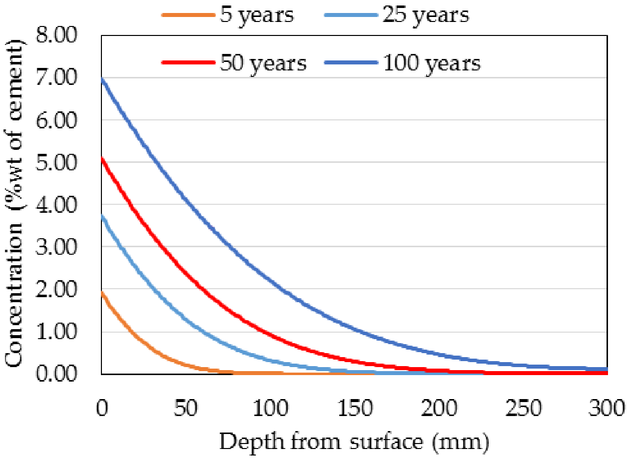

Fig.2: Chloride content variation with depth from surface at 5, 25, 50, and 100 years.

It is obvious that at the same point, chloride ions accumulate with time. It will be considered in this study, the variation of chloride concentration with time at the same point which is chosen here to be the concrete cover value. The concentration variation against time at 35 mm from the surface is shown in Fig. 3.

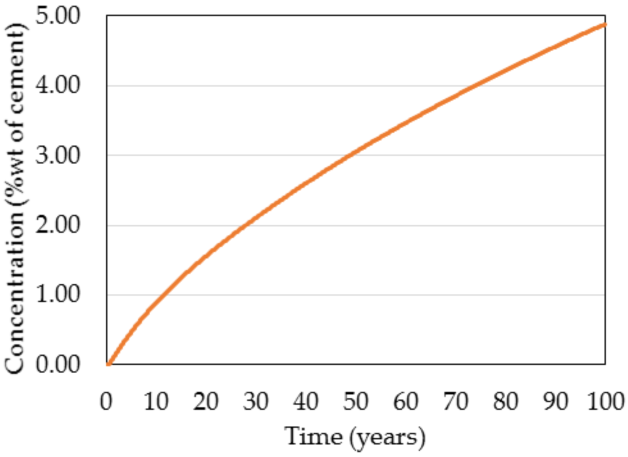

Fig.3:Variation of chloride concentration with time at 35 mm from concrete surface.

3.1.2 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. According to the model selected, the change in *w/c* affects the value of reference diffusion coefficient D_{28}. Values of D_{28} for each value of *w/c* are shown in Table 2. The chloride content variation with time at distance of 35 mm from the concrete surface for each value of *w/c* along with the reference value 0.40 is shown in Fig. 4.

It is noticed as expected that the chloride ingress is directly proportional to the w/c ratio i.e. at certain time, increasing w/c leads to an increase in the predicted value of concentration and vice versa.Also, the effect of *w/c* change on concentration is more obvious in *w/c* range of 0.20-0.40 than 0.40-0.60. The rate of increase or decrease in concentration *C* with respect to the reference concentration C_{ref} corresponding to *w/c* of 0.40 is shown in Fig. 5.

Table 2:Values of diffusion coefficient for different w/c ratios.

w/c	0.20	0.25	0.30
$D_{28}(m^2/s)*10^{-12}$	2.63	3.47	4.57
w/c	0.35	0.40	0.45
$D_{28}(m^2/s)*10^{-12}$	6.0	7.94	10.5
w/c	0.50	0.55	0.60
$D_{28}(m^2/s)*10^{-12}$	13.8	18.2	29.98

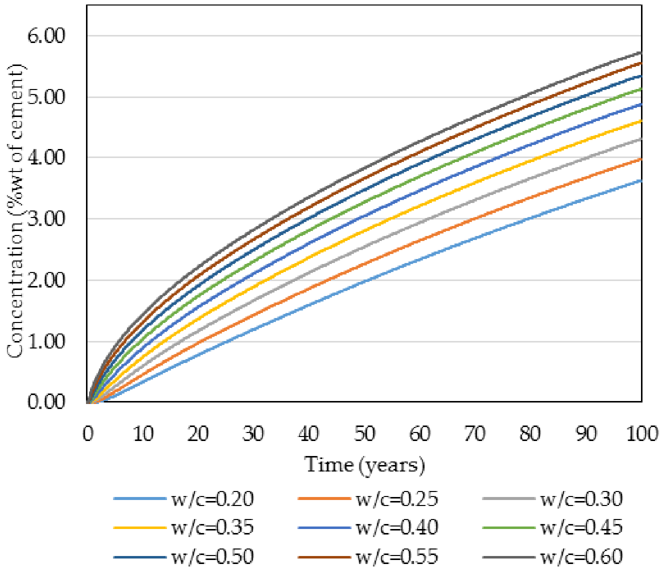

Fig. 4:Variation of chloride concentration with time at 35 mm from concrete surface for different values of w/c ratio.

For a certain value of *w/c*, the rate of change in concentration is higher at early ages up to 10 years, then the rate turns to be much slower. Moreover, the more is the difference between the *w/c* ratio and the reference value, the more is the change ratio in concentration.

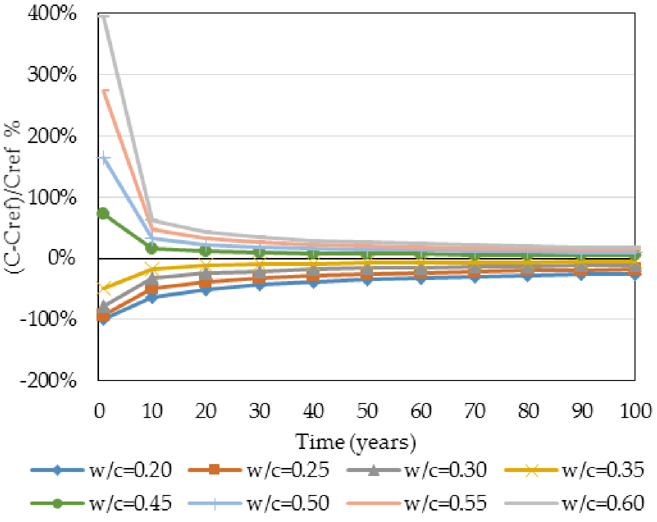

Fig. 5:Change percentage of chloride concentration at 35 mm from concrete surface for each w/c ratio with time.

At 50 years, the change of *w/c* from 0.40 to 0.35 (-12.5%), 0.40 to 0.30 (-25%), and 0.40 to 0.20 (-50%) results in a reduction (increase) of concentration (service life) by about 8%, 16.5%, and 35%, respectively. These ratio are comparable with the reduction ratios of service life obtained from increasing w/c by the same ratios (+12.5%, +25%, and +50%) which are 7.35%, 14% and 30.5%. These values are smaller than the former because the effect of w/c is more obvious in the range (0.20 to 0.40) than (0.40 to 0.60) as indicated in Fig. 4.

3.1.3 ConcreteCover (*cov*) Effect

It is well known that concrete cover is the barrier that keeps harmful substances away from the steel reinforcement. Its effect is evaluated by keeping all reference values constant and changing the cover value from 20 to 60 mm with a step of 5 mm, the variation of chloride concentration with time at a location equals the cover value apart from the concrete surface is plotted for different concrete cover values in Fig. 6. It is observed that at certain time, thechloride content at reinforcement decreases with cover increase. The percentage change in concentration *C* with respect to the concentration at reference cover 35 mm $C_{ref}$is illustrated in Fig. 7. Similar to *w/c* effect, the rate of change in concentration is high only at early times. At 50 years, the reduction of concrete cover from 35 to 30 mm (-14%), 35 to 25 mm (-28%), and 35 to 20 mm (-42%) results in an increase of concentration by 8.1%, 16.7%, and 25.8% respectively, and the increase of concrete cover from 35 to 40 mm (+14% of reference), 35 to 45 mm (+28%), 35 to 50 mm (+42%), and 35 to 60 mm (+71%) results in a reduction of concentration by 7.7%, 15%, 21.8%, and 34.3% respectively.The later ratio are less than the former as the effect of cover change on concentration is more obvious in cover range of 20-35 mm than 35-60 mm.

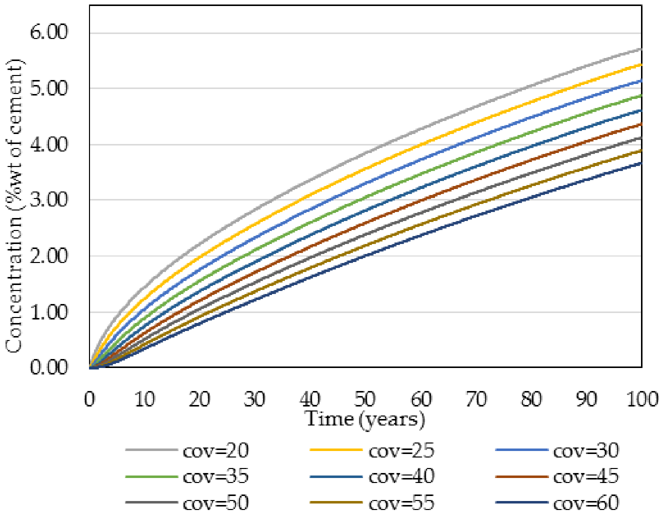

Fig.6: Variation of chloride concentration with time at each value of concrete cover.

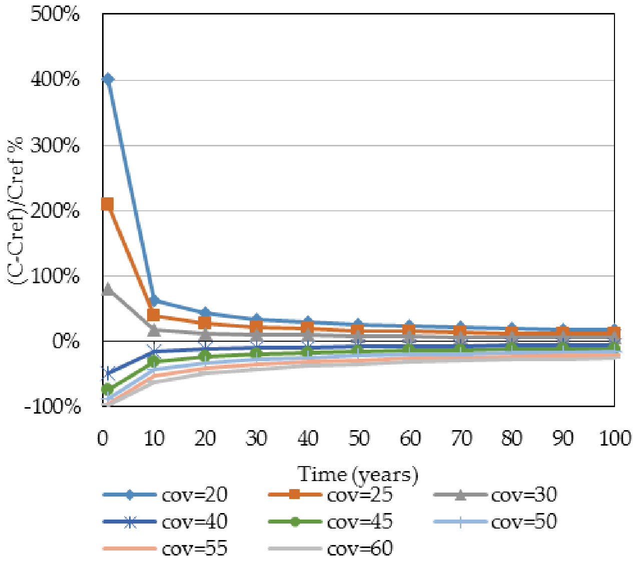

Fig. 7: Change percentage of chloride concentration for each cover value with time.

3.1.4 Effect of Fly Ash and Slag Addition

The effect of fly ash and/or blast-furnace slag addition is considered through the age factor, *m*. The value of *m* is changed from 0.20 to 0.60 with a step of 0.05. The time variation of concentration at 35 mm from the surface for different values of *m* is represented in Fig. 8. It is obvious that increasing the age factor reduces considerably the concentration value. Recalling that the reference value of m is 0.2, the change of chloride concentration *C* with respect to that of the reference value C_{ref} is depicted in Fig. 9. The change in concentration follows a nearly constant rate from initial ages. At 50 years, percent of concentration reduction (or service life increase) due to an increase of age factor by 25%, 50%, 75%, 100%, 125%, 150%, 175%, and 200% are 8%, 16.65%, 25.7%, 35%, 44.4%, 53.7%, 62.45%, and 70.75% respectively.

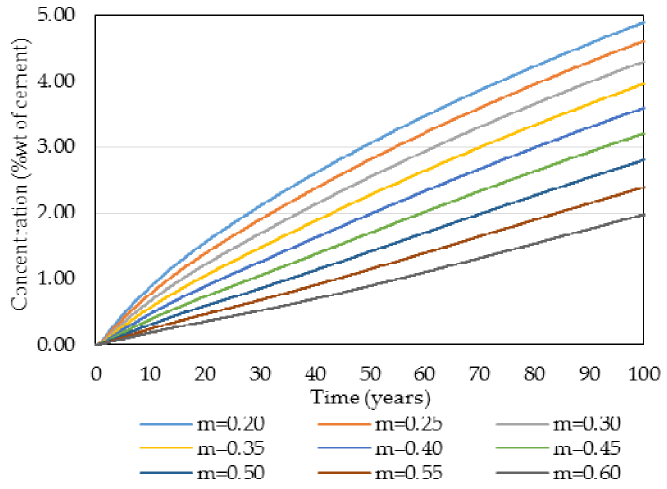

Fig.8: Variation of chloride concentration with time at 35 mm from concrete surface for different values of age factor.

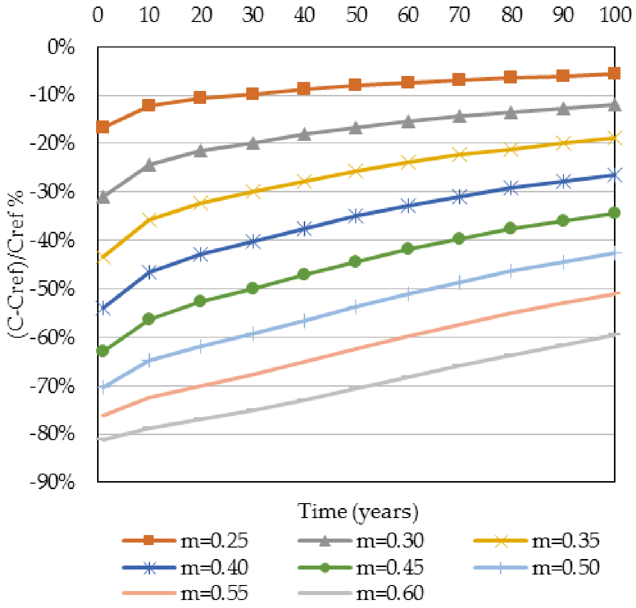

Fig. 9:Reduction percentage of chloride concentration at 35 mm from concrete surface for each value of age factor with time.

3.1.5 Effect of Silica Fume (*SF*) Addition

The effect of silica fume is considered by multiplying the reference diffusion coefficient by a factor$e^{-0.165*SF}$. The percentage of silica fume is used as 5%, 10%, and 15%. The modified values of $D_{28}$are 3.48E-12, 1.53E-12, and 6.68E-13 m^2/s, respectively. The variation of chloride concentration with time at 35 mm from surface isillustrated for each percentage of silica fume along with the reference value 0% in Fig. 10.The addition of silica fume increases the service life considerably. At 50 years, the addition of 5%, 10%, or 15% of silica fume results in a reduction of concentration by about 25.5%, 54.5%, and 80.6% respectively.

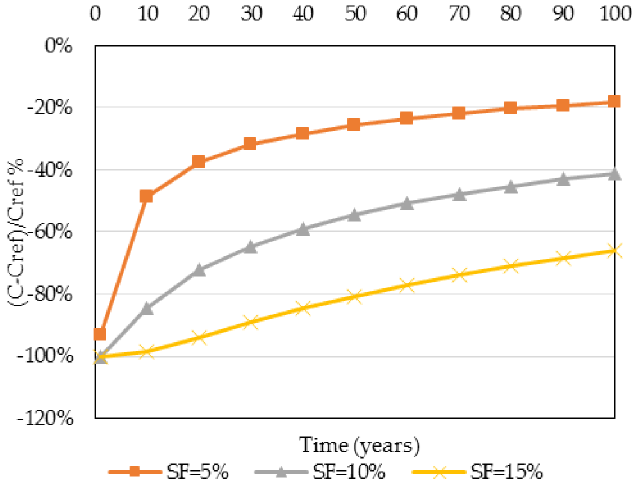

Fig.10: Variation of chloride concentration with time at 35 mm from concrete surface for each value of silica fume

Fig. 11 shows the reduction percentage of chloride concentration C due to added values of silica fume with respect to that of the reference value C_{ref}.

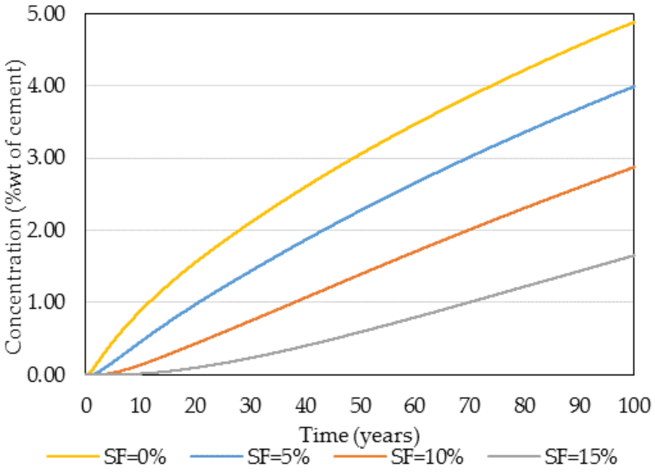

Fig.11: Reduction percentage of chloride concentration for different values of silica fume with time.

3.1.6 Effect of Ambient Temperature (T)

The effect of ambient temperature is considered by multiplying the reference diffusion coefficient by a factor $F(T)$. The numerical simulation is carried out for temperature values of 25°C, 30°C, and 35°C respectively. The values of $F(T)$ are 1.272, 1.673, and 2.137 respectively. The time variation of chloride concentration at 35 mm is illustrated in Fig. 12 for different values of ambient temperature. The change in concentration C relative to that of the reference value C_{ref} at ambient temperature of 20°C at each ambient temperature value is shown in Fig. 13.

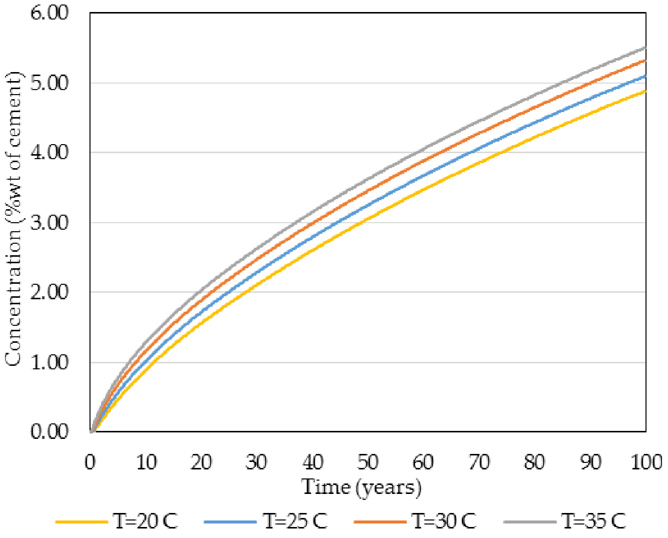

Fig.12:Variation of chloride concentration with time at 35 mm from concrete surface for different values of ambient temperature

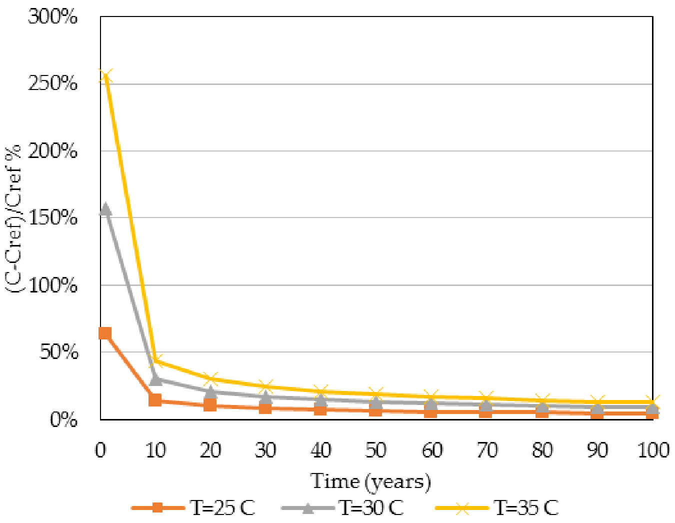

Fig. 13: Increase percentage of chloride concentration at 35 mm from concrete surface for different values of ambient temperature

Temperature change from 20 to 25 (25%) increases the concentration at 50 years by 6.45%. Increase by 50% and 75% changes the value of concentration by 13.2% and 18.7%.

3.1.7 Effect of Relative Humidity (RH)

The effect of relative humidity is considered by multiplying the reference diffusion coefficient by a factor$F(T)$.The RH values ranged from 50% to 75% with a step of 5%. The value of$F(T)$ for each RH value is shown in Table3. The time variation of chloride concentration at 35mm from concrete surface is plotted for different values of RH along with the reference value of 100% in Fig. 14.

Table 3: Values of $f\,(RH)$ for different RH values.

RH (%)	50	55	60
F(RH)	0.0588	0.08697	0.1324
RH (%)	65	70	75
F(RH)	0.2065	0.3254	0.5

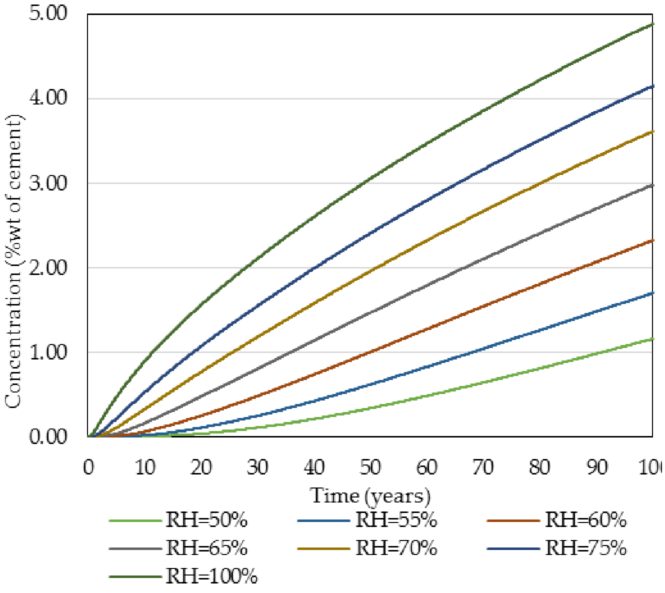

Fig. 14:Variation of chloride concentration with time at 35 mm from concrete surface for different values of relative humidity.

The reduction of chloride concentration *C* with respect to that of the reference value $C_{ref}$is illustrated in Fig. 15. Also, the ratios of reduction in concentration corresponding to reduction of 25%, 30%, 35%, 40%, 45%, or 50% in *RH* at 50 years are 21.17%, 35.88%, 52%, 67.2%, 79.8%, and 89%. 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.

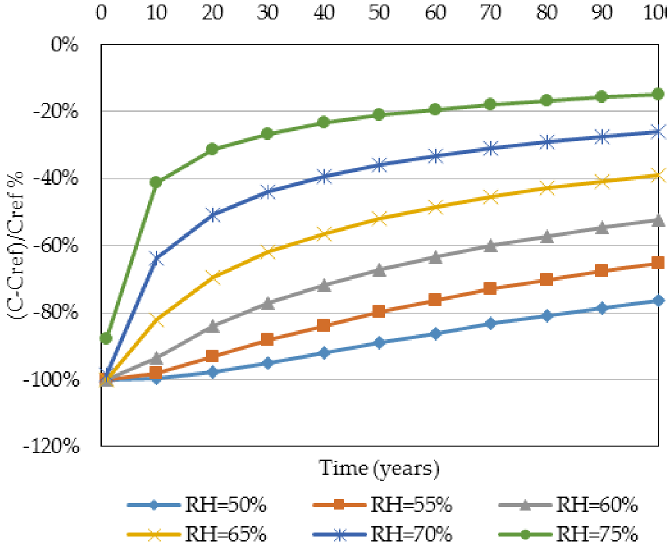

Fig.15:Reduction percentage of chloride concentration at 35 mm from concrete surface for different values of relative humidity.

IV. CONCLUSIONS

In this paper, the effect of different parameters on one-dimensional chloride ion diffusion and corrosion initiation time is studied, and the following is concluded:

1- Service life is inversely proportional to water to cement ratio. 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 8% - 35%, and by 7.35%-30.5%in range of 0.40-0.60.

2- The service life is directly proportional to the concrete cover. The variation in concrete cover in the range of 20-35 mm by 14%-42% changes the service life by 8.1%-25.8%, and in the range of 35-60 mm by 7.7%-21.8%.

3- The addition of fly ash and blast-furnace slag is recommended as they increase the age factor*m*, as a result, the increase of *m* by 25% - 200% increases the service life by 8%-70.7%. Also, the addition of silica fume by 5%-15% increases the service life by 25.5%-80.6% and indicating a significant effect on service life.

4- Temperature increase reduces service life. Increase of temperature by 25%-75% reduces service life by 6.45%-18.7%. Also, relative humidity has a significant effect on chloride ion diffusion, and should not be overlooked when predicting service life of a structure at a certain location. Reduction of relative humidity increases the service life and reducing it by 25%-50% increases the life by 21.2%-89%.

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