EVALUAREA DEPENDENȚEI DE TIMP A COEFICIENTULUI DE DIFUZIE A IONILOR DE CLORURĂ ŞI A CONȚINUTULUI SUPERFICIAL DE CLORURĂ PENTRU STRUCTURILE DE BETON

EVALUATING TIME DEPENDENT CHLORIDE DIFFUSION COEFFICIENT AND SURFACE CHLORIDE CONTENT FOR CONCRETE STRUCTURES

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Chloride ingress in concrete structures has been defined and modeled using Fick's law of diffusion by many researchers, and most of the researchers considered diffusion coefficient and surface chloride content as constants. Now, it has been recognized that diffusion coefficient (D) and surface chloride content (Cs) varies with the increase in age of the structure. This paper presents a methodology for evaluating the values of D and Cs for concrete structures of different age groups, and also investigated the variation of these parameters with respect to age of structure by using results of a field survey.

Pătrunderea inilor clorură în betonul de structură a fost definită şi descrisă pe baza legil Fick de majoritatea cercetătorilor, şi cei mai mulți cercetători consideră coeficientul de difuzie şi conținutul superficial de clorură ca şi constante. Acum, a fost recunoscut că valorile coeficientului de difuzie, D şi ale conținutului superficial de clorură, Cs, variază cu vârsta structurii de beton. Această lucrare prezintă metodologia de evaluare pentru D şi Cs aferente structurilor de beton, pe diferite grupe de vârstă, şi, de asemenea, s-a investigat variația acestor parametri în ceea ce priveşte vârsta structurii, prin utilizarea rezultatelor unui sondaj teren.

Keywords: *Concrete; Chloride diffusion coefficient; Modeling transport.*

1. Introduction

Ingress of chloride ion in reinforced concrete (RC) structures is topic of concern for the researchers. Significant amount of researches have been performed by researchers to model transportation of chloride ion into concrete structures. Modeling transport of chloride ion in concrete structures by the equations based on Fick's law of diffusion is a most convenient method (Sun et al.) [1]. Fick's second law is considered to be the most practical and elegant method available (Khatri and Sirivivatnanon) [2]. Models based on Fick's second law are developed, considering that chloride ion transportation is influenced by diffusion (Georgescu et al.) [3]. Most of the researchers considered chloride diffusion coefficient and surface chloride content as constants in the well established analytical solution of the Fick's second law of diffusion.

$$C(x,t) = Cs\left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)\right] \quad (1)$$

where C(x,t) is chloride content at depth x and time t; Cs is surface chloride content; D is diffusion coefficient and erf is the well known error function.

$$\mathrm{erf}\,(u) = \frac{2}{\sqrt{\pi}}\int_0^u e^{-t^2}\,dt \quad (2)$$

Diffusion and absorption are the major transport mechanisms governing chloride penetration in concrete structures (Wang et al.) [4]. Equation (1) considered diffusion coefficient and surface chloride content as constants and independent of time. Later it has been observed that they changes with time. In last few years large research efforts have been made to investigate variation of diffusion coefficient and surface chloride content with time and it has been found that these parameters depend on time. Therefore, if constants 'D' and 'Cs' are used for long term predictions it results in gross errors (Costa and Appleton) [5]. Thus, it is very important to evaluate the dependency of these parameters on time or age of the structures (Costa and Appleton) [6]. Surface chloride content and apparent diffusion coefficient for structures have been subjected to ample experimental investigations during past years (Marano et al.) [7]. Several researchers considered D and Cs as variables [1, 5, 8-12] Sun et al. [1] considered the time and depth dependence chloride diffusion coefficient rather than constant, to predict service life of structure based on the analytical solution of Fick's 2nd law of diffusion. Costa and Appleton [5] evaluated time and depth dependence D and Cs for different environmental conditions. Effect of variable curing and environmental conditions on the values of

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these parameters has been presented by Alizadeh et al.[8]. Wang et al. [9] presented the decay of chloride diffusion coefficient with time. Cao and Sirivivatnanon [10] evaluated the dependency of diffusion coefficient on exposed time, temperature and stress factor. Cheung et al. [11] also considered exposure time and environmental conditions dependence surface chloride content. Variable diffusion coefficient has been also considered by Gouping et al. [12].

In this article, values of diffusion coefficient and surface chloride content for different age group of structures have been evaluated. To investigate the effect of time on D and Cs the experimental data obtained from field survey of different structures has been used. The experimental results and study indicate that the surface chloride content increases and diffusion coefficient decreases with the increase in age of the structure, as represented by eqn. (3) and (4) respectively.

$$Cs = a.\ t^{m} \quad (3)$$

$$D = b.\ t^{-n} \quad (4)$$

where t is age of structure; a, b, m and n are empirical constants obtained by curve fitting of data.

2. Methodology to determine Cs and D

From the several surveyed structures located around city of Bhopal, India, concrete structures of age 11 to 60 years have been selected for this study as structures of age up to 10 years are not showing significant variation of these parameters with time. Chloride content as the percentage of weight of concrete has been evaluated at rebar level for the structures of different concrete cover and age by conducting rapid chloride test (RCT) as accepted by ASTM C114. Concrete cover of structures in millimeters (mm) has been measured by using well known cover-meter. Surveyed structures are classified into five groups (G1 – G5) based on their age as presented in Table 1. Average values of age, concrete cover and chloride content have been calculated for each group from experimental data and presented in Table 1.

Graphs are plotted between chloride content at rebar depth and depth from surface which is same as concrete cover, for all the five groups G1 to G5 as shown in Figures 1 to 5. By performing curve fitting of these data relation between chloride content and 'C' and depth 'x' similar to eqn. (5) have been obtained for each group. Negative sign indicates that chloride content decreases with increase in depth from surface.

$$C = -P.\ x + Q \quad (5)$$

where, P and Q are empirical constants. By substituting x=0 in eqn. (5), chloride content at surface of the concrete 'Cs' has been evaluated for each group of structures.

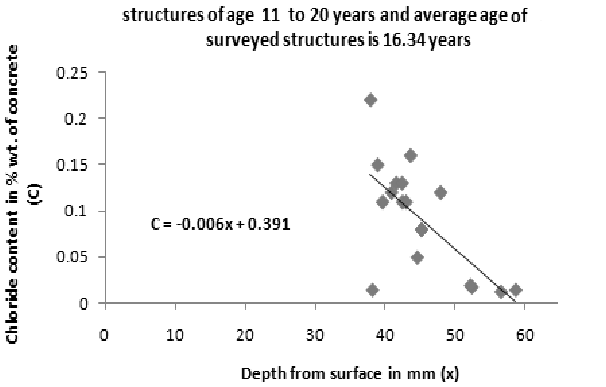

Fig. 1 - Variation of chloride content with time for G1/ *Variația conținutului de clorură, în timp, pentru grupa G1 de betoane.*

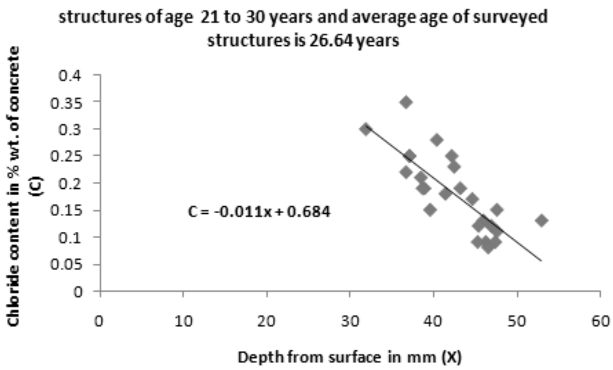

Fig.2 - Variation of chloride content with time for G2 / *Variația conținutului de clorură, în timp, pentru grupa G2 de betoane.*

Table 1

Details of the structures surveyed / *Caracterizarea structurilor de beton studiate*

S. No.	Group *Grupa de betoane*	Age group (years) *Vârsta grupei (ani)*	No. of structures *Nr. structuri*	Average age of structures (years)/*Vârsta structurii de beton (ani)*	Average concrete cover / *Grosimea medie a stratului de beton care acoperă armătura (mm)*	Average chloride content at rebar depth (% wt. of concrete) *Conținutul de clorură (%din masa betonului)*
1	G1	11 to 20	18	16.34	45	0.092
2	G2	21 to 30	25	26.64	42.47	0.182
3	G3	31 to 40	16	35.5	43.66	0.253
4	G4	41 to 50	12	46.42	43.85	0.292
5	G5	51 to 60	13	56.54	46.69	0.334

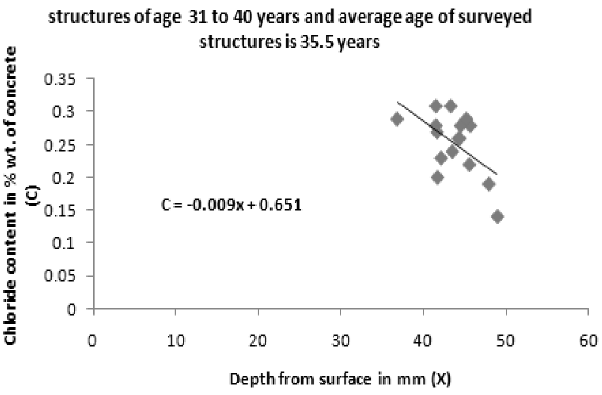

Fig.3 - Variation of chloride content with time for G3 / *Variația conținutului de clorură, în timp, pentru grupa G3 de betoane.*

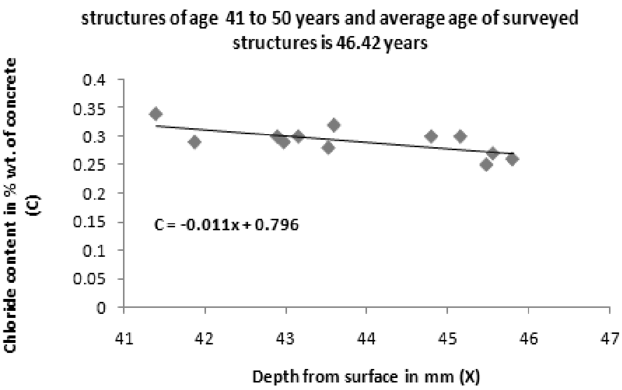

Fig.4 - Variation of chloride content with time for G4/ *Variația conținutului de clorură, în timp, pentru grupa G4 de betoane.*

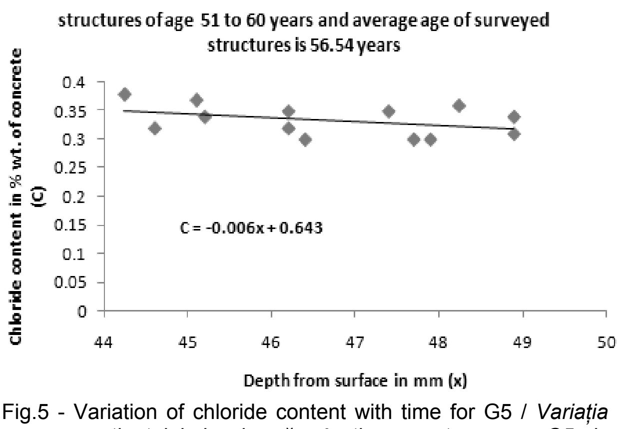

Fig.5 - Variation of chloride content with time for G5 / *Variația conținutului de clorură, în timp, pentru grupa G5 de betoane.*

Table 2, presents the relation between chloride content and depth from surface obtained by curve fitting, for each group of structures as shown in figures 1 to 5. It also presents the value of Cs obtained by substituting x = 0, in these equations.

After obtaining the value of Cs for each group of structures, value of diffusion coefficient 'D' for these groups is evaluated by applying equation (6) obtained from Fick's second law of diffusion.

Table 2

Relation between C and x, and value of Cs
Corelații între C și x, și valoarea Cs

S. No.	Group	Relation between C and x	Cs (% wt. of concrete)
1	G1	C = -0.006 **x** + 0.391	0.391
2	G2	C = -0.011 **x** + 0.684	0.684
3	G3	C = -0.009 **x** + 0.651	0.651
4	G4	C = -0.011 **x** + 0.796	0.796
5	G5	C = -0.006 **x** + 0.643	0.643

Table 3

Evaluated value of D for each group /*Valoarea coeficientului de difuzie, D, pentru fiecare grupă de beton*

S. No.	Group	D x 10^{-12}(m^2/sec)
1	G1	1.394
2	G2	0.966
3	G3	1.455
4	G4	0.819
5	G5	1.473

$$D = \frac{C_{c,avg.}^2}{4\,T_{avg.}}\left[\mathrm{erf}^{-1}\left(1-\frac{C_{avg.}}{C_s}\right)\right]^{-2} \quad (6)$$

where Cc,avg. is average value of concrete cover in mm, Cavg. is average value of chloride content at rebar depth and Tavg.is average age of the structures. So diffusion coefficient for each group has been calculated using eqn. (6) and values from Table 1 and Table 2. Values of D evaluated in m^2/sec, for each group of structures have been presented in Table 3.

3. Time dependence of surface chloride content

By plotting graph between surface chloride content and average age of each group, and by curve fitting of this data relation between Cs and age of the structure is obtained as shown in Figure 6 and the relation is shown in equation (7).

$$Cs = 0.135\, t^{0.432} \quad (7)$$

This relation is similar to eqn. (3), where a= 0.135 and m= 0.432. From eqn. (7) it has been observed that surface chloride content increases with the increase in age of the structure.

4. Time dependence of diffusion coefficient

Relation between diffusion coefficient and age of structure has been obtained by plotting graph between surface chloride content and average age of each group and performing curve

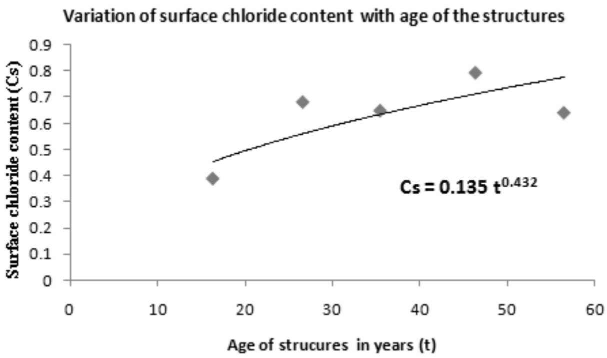

Fig. 6 - Relation between D and t/ *Variația concentrației de clorură la suprafața betonului, Cs, în funcție de vârsta, t.*

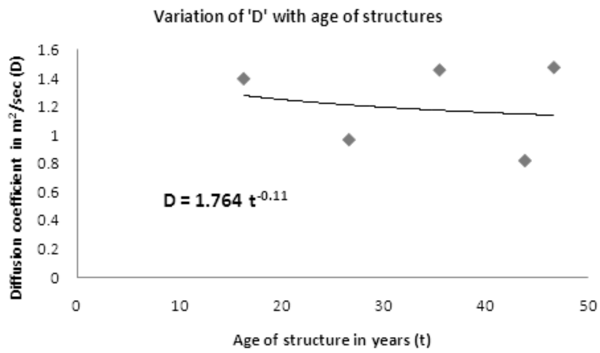

Fig. 7 - Relation between D and t/ *Variația coeficientului de difuzie, D, în funcție de vârsta, t, a betonului.*

fitting of this data, as shown in Figure 7 and the relation is shown in equation (8).

$$D = 1.764\ t^{-0.11} \quad (8)$$

This relation is similar to eqn. (4), where b= 1.764 and n= 0.11, from eqn. (8) it has been observed that surface chloride content decreases with the increase in age of the structures.

4. Conclusions

Ingress of chloride in concrete structures has been defined using Fick's second law of diffusion. Normally diffusion coefficient and surface chloride content are considered to be constant. However, the present study indicates that the diffusion coefficient and surface chloride content depends on the time.

Structures of age between 11 and 60 years have been selected for this study, Chloride content at rebar level and concrete cover of different structures has been evaluated using rapid chloride test and cover-meter. Surveyed structures are classified into five groups (G1 – G5) according to the age group as shown in Table 1. Surface chloride content and diffusion coefficient for each group of structures have been evaluated and presented in Table 2 and table 3. It has been observed from, eqn. (7) and (8) that the surface chloride content increases and diffusion coefficient decreases with the increase in age of the structures. These values of D and Cs can be used by the researchers to evaluate chloride content of concrete structures of different age at depth 'x' and time't'.

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