Pergamon

Cement and Concrete Research, Vol. 25, No. 1, pp. 187-196, 1995

0008-8846/95 $9.50+.00

0008-8846(94)00126-X

C-D-c-t DIAGRAMS FOR PRACTICAL DESIGN OF CONCRETE DURABILITY PARAMETERS

Dubravka Bjegović[1], Vedrana Krstić[2], Dunja Mikulić[1], Velimir Ukrainczyk[1]

[1] Department of Materials, Faculty of Civil Engineering, University of Zagreb, Kačićeva 26, Zagreb 41000, Croatia

[2] Department of Structural Engineering, Faculty of Civil Engineering, University of Zagreb, Kačićeva 26, Zagreb 41000, Croatia

(Refereed)
(Received March 17, 1994)

ABSTRACT

Structures (especially bridges), in Croatian coastal marine environment, are exposed to influence of different aggressive factors. Since many old structures have to be repaired and since many new have to be constructed in that area, there is a special interest of both, experts and the public to perform works with high quality standards. In this paper we propose a method for durability design of structures built in marine environment based on space and time distribution of chloride ions in reinforced concrete structures. This method, which is developed as the computer program CHLODIF, is applied during the construction of new Maslenica bridge.

Introduction

Reinforced concrete is one of the most durable material if it is applied in convenient environment conditions. However, in aggressive environment conditions (marine environment) durability of reinforced concrete structures may be significantly reduced. In this case, impossibility of taking over environmental loads annuls otherwise good physical or mechanical characteristics of reinforced concrete. Structures damaged in this way, usually require extremely large finances for their repair programs.

In Croatian coastal area there are many bridges in very poor conditions. Corrosion of steel in concrete has damaged Pag bridge significantly. The last inspection of Krk bridge showed that we have to seriously consider a possibility of repairing some parts of this the largest arch bridge in the world. All these facts stimulate authors of this paper to pay more attention to durability problem of new Maslenica bridge, especially to problem of steel corrosion in concrete. At the Faculty of Civil Engineering in Zagreb, an expert team working on the problem of durability of reinforced concrete [1, 2] worked out a computer program CHLODIF that can help in solving these problems. CHLODIF is based on space and time distribution of chloride ions diffusion in reinforced concrete structures and gives proposals for concrete properties and estimates a service life of structures exposed to aggressive influence of chloride ions.

In this paper, fundamental principles of diffusion process of chloride ions in concrete are presented, which is base of main CHLODIF algorithm. Some output results obtained by this program are also showed.

Fundamental Principles of Chloride Ions Diffusion Process in Reinforced Concrete Structures

Absorption, permeability and diffusion are three fundamental transmission processes by which chloride ions can enter and pass through reinforced concrete structures. Although all of them contribute to increase Cl^- concentration, diffusion is the main distributive process and it is discussed in this paper.

One-dimensional mathematical model of non-steady diffusion process in anisotropic and inhomogenous materials, such as reinforced concrete, is described by second Fick's law [3].

Solution of this partial differential equation of diffusion for a semi-infinite medium is usually given by:

$$C(x,t) = C_0\left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D \cdot t}}\right)\right] \quad (1)$$

where $C(x,t)$ - chloride ions concentration at distance x after time t
C_0 - initial concentration
D - diffusion coefficient
$\mathrm{erf}\left(\frac{x}{2\sqrt{D \cdot t}}\right)$ - the error function.

In order to develop a practical method for durability parameters' design of structures exposed to marine environment we gave the following meanings to the members of equation (1):

C_0 - load (initial Cl^- concentration)
D_{Cl^-} - material property (chloride diffusion coefficient)
x - up to concrete cover (0 - c)
t - up to initial time of reaching C_{cr} at c (0 - t_0)
C_{cr} - criterion (0.4% on cement weight - initial corrosion concentration).

Initial chloride ions concentration - C_0

Initial concentration of chloride ions is taken as the concentration in surface layer of concrete within thickness of 2-5 mm. With supposition that capillary pores in concrete can be completely filled with sea salt, quantity of chloride ions in relation to mass of cement per $1m^3$ of concrete is

$$Cl^- = \frac{V_c}{C} \cdot q \quad (\%) \tag{2}$$

where V_c - volume of capillary pores
C - quantity of cement per $1m^3$ of concrete
w/c - water cement ratio
h - degree of hydration
q = 112.33 - number obtained from quantity of NaCl, $MgCl_2$ and $CaCl_2$ in sea water and quantity of Cl^- in NaCl, $MgCl_2$ and $CaCl_2$ (see Appendix).

Volume of capillary pores - V_c

Volume of capillary pores can be calculated according to [4]

$$V_c = [(w/c)-0.382 \cdot h] \cdot C \ . \tag{3}$$

Theoretically, capillary volume changes according to equation (3), for three cement hydration degrees, two cement quantities and three water-cement ratios are given in Table 1.

Table 1 Volume of Capillary Pores in Concrete, V_c

cement (kg/m^3) ☞	300			360		
w/c ☞	0.45	0.42	0.40	0.45	0.42	0.40
hydration degree (h) ☟	**V_c (dm^3/m^3)**					
0.4	89.16	80.16	74.16	106.99	96.19	88.99
0.5	77.70	68.16	62.70	93.24	82.44	75.24
1.0	20.40	11.40	5.40	24.48	13.68	6.48

Volumes of capillary pores given according to equation (3) with assumption h=1, according to the literature [5], and according to our own experiments [5], are compared in Table 2.

Table 2 Chloride Ions Content in Concrete Skin (C_{Cl^-} % on cement weight)

C_{Cl^-} (%)		
Calculated	Literature	Experiments
2 - 25	2 - 10	2.5 - 7.5

For one of considered mix designs of Maslenica bridge (Table 3 [6]) these results are given in Table 4.

Table 3 Concrete Mix Proportions for Arch Abutments

CONSTITUENT	QUANTITY	
Blended PC (30% blast-furnace slag)	300	kg
Aggregate	1922	kg
Water	131.9	kg
Air	4.0	%
w/c	0.44	
Superplasticizer	2	%

Table 4 Chloride Ions Content in Surface Layer of Concrete in Relation to Cement Quantity for One of Considered Mix Designs of Maslenica Bridge

		V_c (dm^3)	Cl^- (%)
w/c = 0.44	C = 300 kg h = 1	17.40	6.52

Chloride ions diffusion coefficient - D_{Cl^-}

Diffusion coefficient is material parameter, but it is different for each diffusing substance. Usually, the recommended values for chloride ion diffusion coefficient in concrete are in range of 10^{-7} cm^2/s and more for concrete of poor quality, to 10^{-9} cm^2/s and less for concrete of good quality.

According to the research carried out by Takewaka and Mastumoto [7], the following expression for calculating the chloride diffusion coefficient in concrete is proposed:

$$D_{Cl^-} = D_{w/c} \cdot D_1 \cdot t^{-0.1} \tag{4}$$

where $D_{w/c}$ - coefficient that takes into account the influence of water cement ratio
D_1 - coefficient that takes into account the type of cement
t - exposure period.

In that case, D_{Cl^-} is time dependent coefficient, so we used the next transformation to eliminate it:

$$\tau = \int_0^t D_{Cl^-}(s)\,ds\ . \tag{5}$$

Now, we have to solve a modified diffusion problem given by:

$$\frac{\partial C}{\partial \tau} = \frac{\partial^2 C}{\partial x^2} \tag{6}$$

where, in the most simple approximation, we change the error function variable from equation (1) in $\left(\frac{x}{2\sqrt{\tau}}\right)$.

CHLODIF - Computer Program for Simulation of Chloride Ions Diffusion Process into the Concrete

Computer program CHLODIF is created with a basic purpose of chloride ions diffusion process simulation in time and space in reinforced concrete structures with possibility of service life prediction. It is continuation of "Difcl" program [2].

CHLODIF is primarily intended for a durability design of new structures when measuring data of diffusion coefficient and initial concentration of chloride ions don't exist or these data are insufficient or unreliable.

The main algorithm of program is based on numerical solution of diffusion equation (6) taking into account limited number of the error function members. Secondary algorithms determine initial concentration and initial value of chloride ions diffusion coefficient. Flow chart of program is shown in Fig. 1.

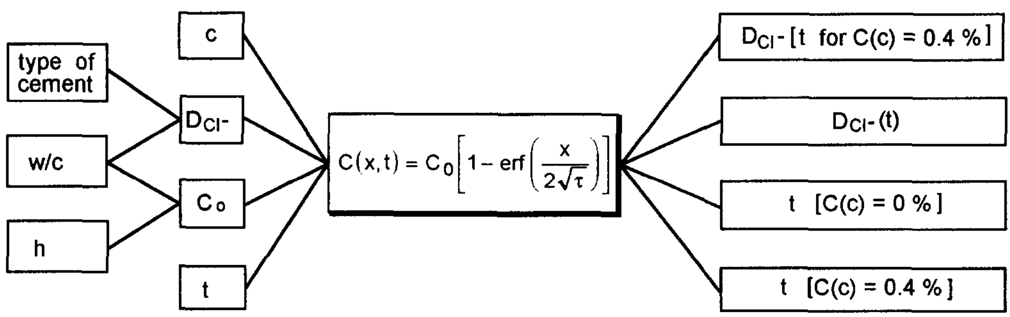


Fig. 1 Flow chart of CHLODIF

CHLODIF makes possible to find out a solution of time and space chloride ions distribution into concrete and to predict service life of reinforced concrete structures. In this case, it is supposed that designer knows value of load C_0, which is realistic supposition in view of many existing data from structures built in similar conditions [5].

In addition, CHLODIF makes possible C-D-c-t diagram creations (C-D-c-t nomograms for design) (Fig. 2) that give four possibilities in durability design [8] (Table 5).

Table 5 Four C-D-c-t Diagrams Possibilities

VARIABLES	C-D-c-t DIAGRAMS POSSIBILITIES			
	I	II	III	IV
c	⇔	☝	designed 💻	designed 💻
D_{Cl^-}, a, k	💻	designed 💻	💻	designed 💻
C_o; C_{cr}	⇔	✓	✓	✓
t	designed 💻	☝	☝	☝

⇔ measured ☝ required
💻 calculated ✓ allowed

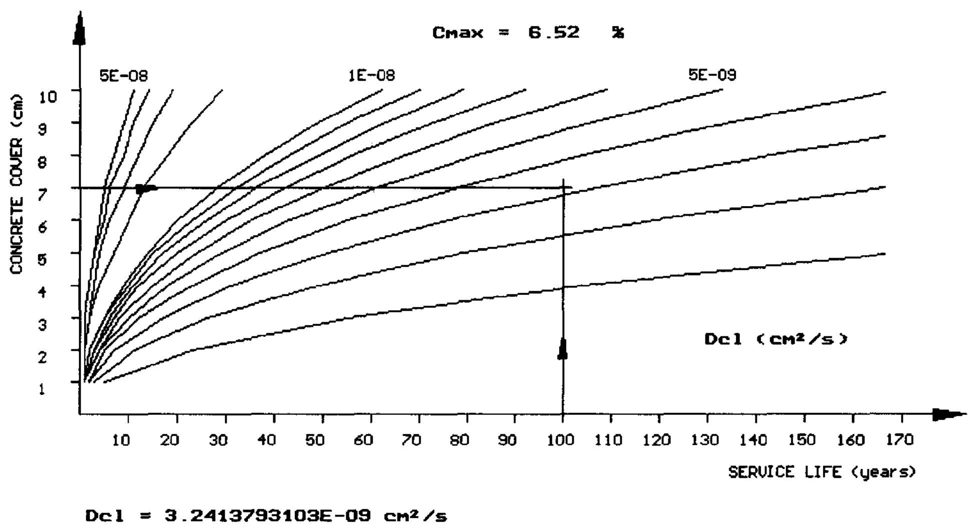


Fig. 2 C-D-c-t diagram

Possibility I. Diagnosis of existing reinforced concrete structures conditions.

By testing samples taken from the structure, flow of aggressive media (Cl^-, CO_2, etc.) through cover depth (c) and around the reinforcement is obtained. On the basis of these data, diffusion coefficient (D_{Cl^-}), absorption coefficient (a) and permeability coefficient (k) are calculated and structure service life (t) is predicted.

Possibility II. Calculation of penetrability parameters (D_{Cl^-}, a, k) for expected structure service life (t) and given dimension of cover (c).

Possibility III. Design of cover depth (c) for the expected structure service life (t) and given penetrability parameters (D_{Cl}^-, a, k).

Possibility IV. Optimizations of penetrability parameters (D_{Cl}^-, a, k) and cover depth (c) for given structure service life (t).

Which of these four possibilities will be analyzed depends on age and state of reinforced structure.

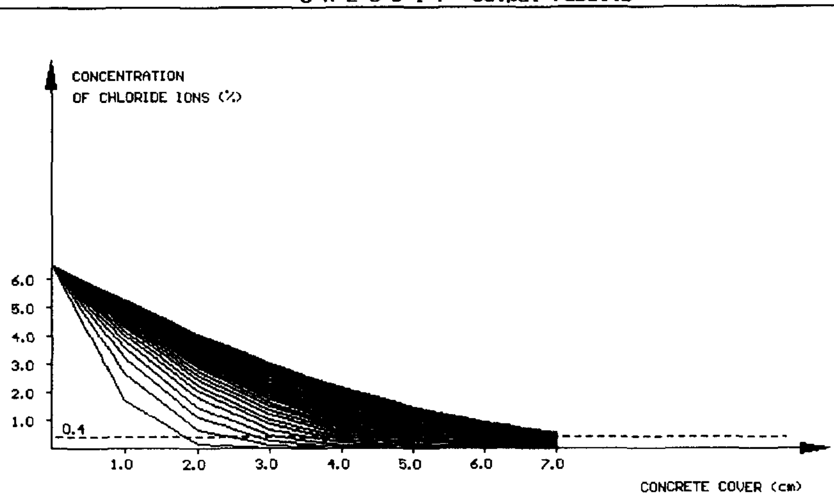
Durability Properties Design for Maslenica Bridge

Program CHLODIF is applied in designing the quality of material, cover depth and service life prediction of new Maslenica bridge. Practical application of CHLODIF can be shown on the example of arch abutments that are the most exposed parts of the bridge.

Concrete mix proportion for arch abutments is shown in Table 3.

On the basis of measured data from similar structures and our experiments and detailed calculations for this object [5], chloride ions diffusion process can be analyzed up to 7 cm depth (one of considerated cover values; for this value cover is additionally reinforced by plastic fibers) and for initial concentration C_0 = 6.52 % . Chloride ion diffusion coefficient, D_{Cl}^- , can be determined by program on the basis of equation (4). Observation time interval is 30 years. Output results of CHLODIF are shown in Fig. 3.

C H L O D I F output results



water/cement ratio	0.44	total observation time T (years)	30
concrete cover c (cm)	7.00	time for C(c) = 0.0 % (years)	2
Dcl (t = 1 year)	1.1137847222E-08	time for Ccr(c) = 0.4 % (years)	25
Dcl for C(c) = Ccr	8.0724851638E-09	Co (%)	6.52
Dcl (T = 30 years)	7.9266399341E-09	C(c, T) (%)	0.563

Fig. 3 CHLODIF output results

On the basis of given output, after 25 years in depth of 7 cm, the value of 0.4 % per cement quantity of chloride ions concentration will be achieved. It means that in maintenance project at this time one have to anticipate and apply adequate additional protection of this structure.

If one considers that time t_0 = 25 years is inadequate, he can use C-D-c-t diagram (Fig. 2) in a way to modify concrete quality (the diffusion coefficient D_{Cl^-}) or concrete cover (c) for the same initial concentration C_0 = 6.52 % (possibility III).

It means that for arch abutments service life of 100 instead of 25 years one can find out from diagram in Fig. 2 amount of D_{Cl^-} that is $3.24 \cdot 10^{-9}$ cm²/s (before $D_{Cl^-} = 8.07 \cdot 10^{-9}$ cm^2/s). Concrete cover c = 7 cm that is the same like before.

Conclusions

Computer analysis of steel corrosion in concrete in the phase of designing is the most effective and the cheapest way that makes possible to evaluate different protection measures of the structure during its maintenance period and to draw out a timetable of their application.

Performed analysis of concrete quality, cover depth and service life prediction of reinforced concrete structure of new Maslenica bridge has shown that explained numerical simulation of corrosion process could be successfully applicable in durability design of these and similar structures.

Appendix

Calculation of initial chloride ions concentration

For the Adriatic sea water composition, that is given in Table 6, quantities of particular salts are:

$NaCl$ 78.3%
$MgCl_2$ 9.4%
$MgSO_4$ ... 6.4%
$CaSO_4$ 3.9%
$CaCl_2$ ..... 1.7% .

For calculation of total Cl^- quantity in concrete, first we have to determine a quantity of competent salts.

Densities of the competitive salts are [9]:

$$\rho_{NaCl} = 2.165 \quad kg/dm^3$$
$$\rho_{MgCl_2} = 2.316 \quad kg/dm^3$$
$$\rho_{CaCl_2} = 2.512 \quad kg/dm^3$$

and if V_c is volume of capillary pores in concrete given in (dm^3) that can be completely filled by salts, their quantities are:

$$M_{NaCl} = V_c \cdot 0.783 \cdot \rho_{NaCl} = V_c \cdot 0.783 \cdot 2.165 = M_{Cl} + M_{Na} = M_{Cl} + \frac{1}{1.542} M_{Cl} \quad (kg)$$

$$M_{MgCl_2} = V_c \cdot 0.094 \cdot \rho_{MgCl_2} = V_c \cdot 0.094 \cdot 2.316 = 2 \cdot M_{Cl} + M_{Mg} = 2 \cdot M_{Cl} + \frac{1}{1.459} M_{Cl} \quad (kg)$$

$$M_{CaCl_2} = V_c \cdot 0.017 \cdot \rho_{CaCl_2} = V_c \cdot 0.017 \cdot 2.512 = 2 \cdot M_{Cl} + M_{Ca} = 2 \cdot M_{Cl} + \frac{1}{0.885} M_{Cl} \quad (kg) \; .$$

Now we can calculate the quantity of each element in proportion of their atomic numbers (Table 7). Cl^- quantity is given by:

$$M_{Cl} = \frac{V_c \cdot 0.783 \cdot 2.165}{1 + 0.648} + 2 \cdot \frac{V_c \cdot 0.094 \cdot 2.316}{2 + 0.686} + 2 \cdot \frac{V_c \cdot 0.017 \cdot 2.512}{2 + 1.13} = V_c \cdot 1.1233 \; (kg) \; .$$

Table 6 Average Composition of the Adriatic Sea Water

SALT	CONTENT (mg/l)
NaCl	26 900
$MgCl_2$	3 200
$MgSO_4$	2 200
$CaSO_4$	1300
$CaCl_2$	600
KSO_4, $Ca(CO_3)_2$, MgBr	
Σ	**34 300**

Table 7 Atomic numbers and corresponding ratios for considered elements

ELEMENT	ATOMIC NUMBER	RATIOS
Cl	35.453	-
Na	22.98977	Cl/Na = 1.542
Mg	24.305	Cl/Mg = 1.459
Ca	40.08	Cl/Ca = 0.885

Finally, the quantity of Cl^- according to cement quantity in 1 m^3 of concrete is

$$Cl^- = \frac{V_c}{C} \cdot 112.33 \; (\%) \; .$$

Acknowledgment

The authors wish to acknowledge Mr. Radovan Milčić who made possible for them to get an insight in "Difcl" program.

References

[1] D. Bjegović, Design of Concrete Structures in Chemically Aggressive Environment, Dissertation, Faculty of Civil Engineering, University of Zagreb, p. 292, (in Croatian), 1991.

[2] D. Bjegović, R. Milčić, V. Ukrainczyk, Calculation of Chloride Flow in Concrete, SCSE, Symposium, Special Engineering Structures, Brijunski otoci, pp. 29-37, (in Croatian), (1988).

[3] J. Crank, The Mathematics of Diffusion, p. 414, Seean edition, Brunel University, Axbridge, Clarendon Press, Oxford, 1986.

[4] V. Ukrainczyk, Concrete, Structure, Properties, Technology, p. 305, (in Croatian), in print, 1994.

[5] Croatian Roads, Special Technical Conditions for Concrete of Maslenica Bridge, p. 42 (1993).

[6] D. Mikulić, Theoretical Model of Concrete Quality Assurance (CAMDOC), Dissertation, Faculty of Civil Engineering, University of Zagreb, p. 168, (in Croatian), 1993.

[7] K. Takewaka, S. Mastumoto, Quality and Cover Thickness of Concrete Based on the Estimation of Chloride Penetration in Marine Environments, ACI-SP 109-117, Concrete in Marine Environment, Detroit, pp. 381-400, (1988).

[8] D. Bjegović, R. Milčić, V. Ukrainczyk, Concrete Cover Design, International Seminar, The Life of Structures - The Role of Physical Testing, Ref. 28, Brighton, UK, (1989).

[9] D. Kolbah, Manual for Chemistry, p. 439, Tehnička knjiga, Zagreb, (in Croatian), 1951.