

Corina Sosdean¹, Dinu Gubencu¹, Geert DeSchutter², Liviu Marsavina¹

EXPERIMENTAL DETERMINATION OF CHLORIDE PENETRATION IN CONCRETE WITH REAL CRACKS

EKSPERIMENTALNO ODREĐIVANJE PENETRACIJE HLORIDA U BETONU SA REALNIM PRSLINAMA

Originalni naučni rad / Original scientific paper

UDK /UDC: 620.192.46:691.328

Rad primljen / Paper received: 25.09.2014

Adresa autora / Author's address:

¹⁾ Politehnica University of Timisoara, Department Strength of Materials, Timisoara, Romania, e-mail:

corina.sosdean@yahoo.com

²⁾ Ghent University, Magnel Laboratory for Concrete Research, Department of Structural Engineering, Ghent, Belgium

Keywords

- real crack
- chloride penetration
- crack width
- non-steady state migration test
- factorial experiment

Abstract

It is well known that the presence of cracks in reinforced concrete structures in aggressive environments accelerates rebar corrosion. The influence of real cracks in concrete structures on the penetration of chlorides and the resulting service life is being investigated in this study. Investigations are carried out at the Magnel Laboratory for Concrete Research of Ghent University in Belgium within a bilateral agreement with Politehnica University of Timisoara, Romania. Non-steady state migration tests are realized according to NT BUILD 492 using an electrical field and real cracks in order to determine the chloride profile. Samples with different crack patterns obtained by drilling from a reinforced concrete slab exposed to a simulated accidental failure of the central support and subsequent vertical loading until collapse have been used in the study in order to provide a more realistic image of the geometry of the cracks. The crack widths are measured using the optical microscope. The chloride penetration depth is measured with a colorimetric method on each specimen and the non-steady state diffusion coefficients are determined. For evaluating the parameters which have the most influence on chloride migration on the samples used in this experiment, a two-level factorial experiment is designed and carried out. The results obtained provide a better understanding of the diffusion process when dealing with concrete structures with real cracks.

INTRODUCTION

Even though significant studies were performed in recent years for predicting the durability of concrete structures, chloride induced corrosion in reinforced concrete structures remains one of the major challenges. Due to the fact that

Ključne reči

- realna prslnina
- penetracija hlorida
- širina prsline
- ispitivanje nestacionarne penetracije
- eksperimentalno određivanje faktorijala

Izvod

Dobro je poznato da prisustvo prsline kod konstrukcija armiranog betona u agresivnim sredinama ubrzava koroziju armature. Istraživanja obuhvataju uticaj realnih prsli na betonskim konstrukcijama na penetraciju hlorida i rezultujući radni vek. Istraživanja su izvedena u Magnel laboratoriji za istraživanje betona na Univerzitetu Gant u Belgiji, u okviru bilateralnog sporazuma sa Politehničkim Univerzitetom u Temišvaru, Rumunija. Ispitivanja neravnomerne penetracije izvedena su prema NT BUILD 492 primenom električnog polja i realnih prsline radi određivanja profila sadržaja hlorida. U studiji su upotrebljeni uzorci sa različitim konfiguracijama prsline dobijeni bušenjem slaba armiranog betona koji je bio izložen simuliranom lomu centralnog nosača i naknadnim vertikalnim opterećivanjem sve do kolapsa, radi postizanja realističnije geometrije prsline. Širine prsline su izmerene optičkim mikroskopom. Dubina penetracije hlorida je izmerena kolorimetrijskom metodom na svakom uzorku, a takođe su utvrđeni i koeficijenti nestacionarne difuzije. Radi procene parametara sa najvećim uticajem na prodiranje hlorida u korišćenim epruvetama u eksperimentu, osmišljen je i izveden eksperiment određivanja faktorijala u dva nivoa. Dobijeni rezultati pružaju bolje razumevanje procesa difuzije kod betonskih konstrukcija sa realnim prslinama.

most reinforced concrete structures are cracked either due to extreme loading, aggressive environment or poor workmanship during execution, it is very important to have a better understanding of chloride diffusivity in the cracked concrete.

Researchers use a variety of programs to create cracks in undamaged concrete. Based on the crack preparation method, the reported experimental studies can be divided into two groups: destructive and non-destructive methods. The methods from the first category adopt different mechanical loading techniques to prepare cracks, such as: the wedge splitting test /1-2/, three or four-point bending test /3/, Brazilian splitting test /4-5/, and expansive core method /6/. Non-destructive methods used to generate cracks in concrete include studies based on the positioning and removal of thin copper sheets before final setting of concrete /7-8/, or inducing a crack by saw-cutting concrete cylinders longitudinally, /9/.

Real cracks in concrete have a complex 3D geometry and their influence on transport and degradation mechanisms is not straightforward, therefore very limited investigation of the influence of chloride diffusion on samples with real cracks has been conducted, /10/.

Due to the fact that it is difficult to evaluate the crack effect on chloride diffusion characteristics, many applications using probabilistic approaches have been generally limited to the sound concrete without considering the crack effect. Still, some researchers developed parametric studies of service life in cracked concrete in order to determine the time to durability failure (time to corrosion). Kwon et al. /11/ have considered the cover depth and time-exposure parameter as design factors with varying values. Full parametric studies of the influence of crack width, roughness and the interval of drying-wetting cycles on the chloride profiles at the cracked zone are developed by Ye et al. /12/.

In the present work, a parametric study on the influence of cracks and the existence of rebars in reinforced concrete structures with real cracks subjected to chloride ingress is presented.

EXPERIMENTAL PROGRAMME

Details of specimen

Four kinds of samples have been used in this research: samples without cracks and without rebars (S) (a); samples with cracks and without rebars (SC) (b); samples without cracks and with rebars (SR) (c) samples with cracks and with rebars (SCR) (d), as it can be observed in Fig. 1, where a representative sample from each group is presented.

In order to obtain samples with real cracks, cylinders with 100 mm diameter and 50 mm thickness are drilled from a RC slab 140 mm thick and 1800 mm wide with the total length of 14.30 m. This slab is exposed to an artificial failure of the central support and subsequent vertical loading which generated cracking and finally its collapse. As noticed, the cracks go all the way to the specimens and that is why the crack depth is not being considered in this research.

A concrete class C30/37 with a maximum size of 14 mm of the coarse aggregate is used in order to manufacture the slab. The test set-up and the results for the experimental large-scale test are described in detail in /13-14/.

For the investigation of chloride diffusion parameters, in this study, concrete samples having the average crack width of 0.2 mm are used.

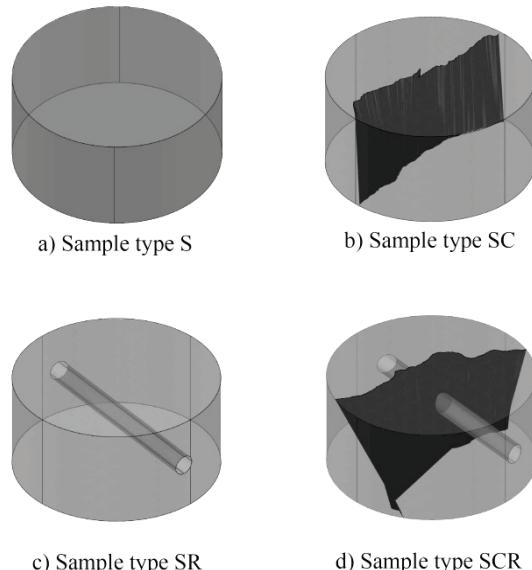


Figure 1. Drilled sample categories.

Slika 1. Primeri izbušenih epruveta

Testing method

A non-steady state migration test is performed on the obtained concrete samples, according to NT BUILD 492, /15/. Before testing, the samples are placed in a vacuum container for vacuum treatment for three hours to a pressure in the range of 10-50 mbar; afterwards with the vacuum pump still running, the container was filled with saturated $\text{Ca}(\text{OH})_2$ solution so as to immerse all specimens which was maintained for a further hour before allowing air to re-enter the container. The specimens are kept in the solution for 18 ± 2 hours.

Afterwards, the samples are placed in the reservoir and an external electrical potential of 30 and 35 V is applied on the samples for 24 h, forcing the chloride ions from the 10% NaCl solution to migrate into the specimens.

Penetration depth

After the test, the samples were split and sprayed with 0.01N AgNO_3 solution and using the colorimetric method, /16/, the chloride penetration profile is determined. The mean penetration profiles on sample categories SC, SR and SCR are determined after cutting the sample perpendicular to the crack path and by measuring the chloride front on each of them. A schematic representation of the procedure is presented in Fig. 2 for sample type SC.

Based on the chloride penetration depth, the chloride migration coefficient (D_{nssm}) can be calculated according to Eq.(1):

$$D_{nssm} = \frac{RT}{zFE} \cdot \frac{x_d - \alpha\sqrt{x_d}}{t} \quad (1)$$

where

$$\begin{aligned} E &= \frac{U-2}{L} \\ \alpha &= 2\sqrt{\frac{RT}{zFE}} \cdot \text{erf}^{-1}\left(1 - \frac{2C_d}{C_0}\right) \end{aligned} \quad (2)$$

C_d – chloride concentration at which the colour changes ($= 0.07\text{N}$);
 C_0 – chloride concentration in the catholyte solution ($= 2\text{N}$)
 erf^{-1} – inverse of error function
 F – Faraday constant ($= 9.648 \times 10^4 \text{ J/V}\cdot\text{Mol}$)
 L – thickness of the specimens (m)
 R – gas constant ($= 8.314 \text{ J/(K}\cdot\text{Mol)}$)
 x_d – chloride penetration depth (m)
 t – test duration (sec)
 T – average value of the initial and final temperatures in the anolyte solution (K)
 U – applied voltage (V)
 z – absolute value of ionic valence ($= 1$ for chloride).

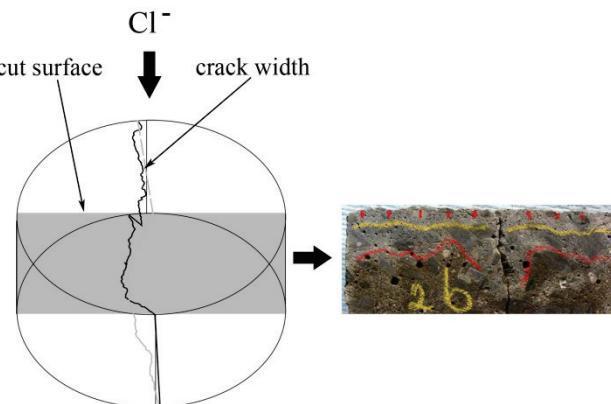


Figure 2. Sample preparation for measuring the chloride front.
Slika 2. Priprema epruvete za merenje fronta hlorida

Figure 3 shows the effect of crack width and rebar position on the diffusion coefficient. It can be easily seen that the migration coefficient increases with the existence of cracks; when increasing the crack width from 0 (sample S) to 0.2 mm (sample SC), the migration coefficient increases from 5.96×10^{-12} to $8.87 \times 10^{-12} \text{ m}^2/\text{s}$. Also it can be observed that the existence of rebars “blocks” chloride diffusion, the migration coefficient decreases to $8.41 \times 10^{-12} \text{ m}^2/\text{s}$. It seems that the lowest value: $7.91 \times 10^{-12} \text{ m}^2/\text{s}$ is registered for samples containing both rebars and cracks. A possible explanation could be the fact that chlorides penetrate along the crack relatively fast up to the top of the crack (crack tip) /17/, but their further propagation is “stopped” by the existence of rebars.

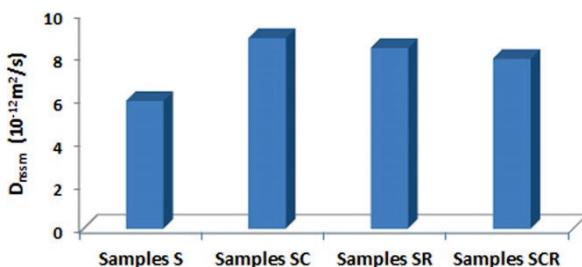


Figure 3. Comparison of diffusion coefficients according to sample type.

Slika 3. Poređenje koeficijenata difuzije prema tipu epruvete

It is important to mention that the values of diffusion coefficients used in this study are mean values.

EXPERIMENTAL INVESTIGATION OF CHLORIDE DIFFUSIVITY IN NON-STEADY STATE MIGRATION

Parametric study of chloride diffusion

Through the above presented experimental programme, it can be observed that the presence of cracks and rebars has an important influence on chloride ingress in cracked samples.

For the parametric study of chloride diffusion a two-level factorial experiment without randomization is designed and carried out in order to determine which of the following parameters: existence of cracks (crack width l) and existence of rebars (rebar no RN) used in the experimental programme has the most influence on chloride ingress in cracked samples subjected to the non-steady state migration test.

The values of the considered parameters, both coded and physical, for each sample together with measured values of the objective function – chloride penetration depth (Dist_Xd) – are presented in Table 1.

Table 1. Experimental matrix.

Tabela 1. Shema eksperimenta

Run no	Levels of influencing factors		Measured values		
	$x_1 \equiv$ crack width l	$x_2 \equiv$ rebar No RN	$y \equiv X_d$		
	coded	(mm)	coded	-	
1	-1	0	-1	0	17.33
2	1	0.2	-1	0	22.48
3	-1	0	1	1	21.21
4	1	0.2	1	1	19.2

RESULT AND DISCUSSION

A standardized Pareto chart is presented in Fig. 4, which allows the hierarchy of both main effects and interaction effect on the response function.

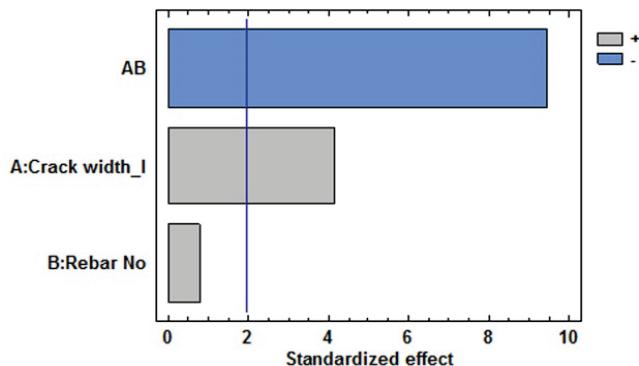


Figure 4. Standardized Pareto chart.

Slika 4. Standardizovana Pareto karta

As it can be observed, the interaction effect of crack width and rebar existence on chloride ingress is the most significant, followed by the existence of cracks. The effect of the rebar presence is not statistically significant on the chloride penetration depth X_d , having a magnitude comparable with the experimental error determined by performing 3 replicas in one experimental point.

It is generally recognized that the existence of cracks provide fast transport routes for chloride. However, crack width can be considered to be one of the most controversial parameters that can influence chloride ingress.

Even though there are different codes prescribing an allowable crack width ranging from 0.05 to 0.3 mm /18-20/, the influence of crack width on concrete properties is still under debate. Gérard & Marchand /21/ show that the steady state migration coefficients of concrete with different crack widths are one order of magnitude higher than for uncracked concrete. While some researchers /22/ suggest the dependence between chloride profiles and crack width, Rodriguez et al. /23/ suggests that chloride diffusion in concrete is independent of the crack width since cracks act as free concrete surfaces and greatly promote chloride ingress, and Marsavina et al. /24/ concludes that the influence of crack on chloride penetration is still not clear and requires further research.

In normal conditions, the cover concrete layer forms a passive film on the surface of the embedded steel surface preventing corrosion. However, under chloride attack, this protective film is disrupted or destroyed, resulting in the corrosion of the rebar. The time period until depassivation is referred to as initiation phase. The existence of cracks accelerates chloride penetration even through fine cracks, inducing corrosion initiation.

According to Subramaniam /25/, when a crack in concrete intersects the steel reinforcing bar, it allows easy ingress of chloride ions, oxygen and water to the steel surface, which results in a faster initiation of corrosion.

It is important to mention that the rebar position in the samples taken in consideration was neglected.

The Eq.(3) of the fitted model is presented:

$$X_d = 20.055 + 0.785l + 0.15RN - 1.79/RN \quad (3)$$

Using the model achieved, the response surface of the dependent variable for the influencing factors is represented in Fig. 5.

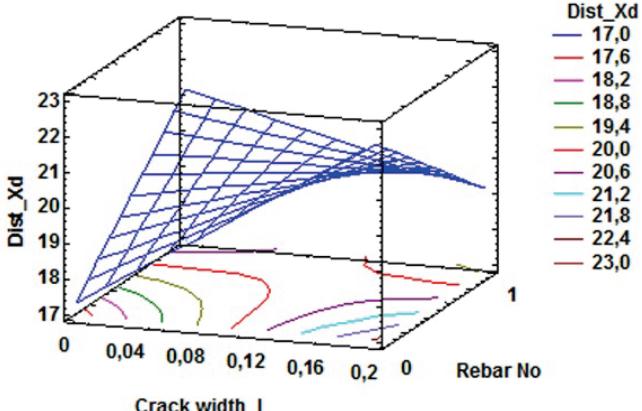


Figure 5. Response surface for chloride profile.

Slika 5. Površina odziva za profil hlorida

CONCLUSIONS

The effects hierarchy and the achieved experimental model show that even if the increase of crack width has led to the enlargement of the chloride penetration depth, it seems that the combined effect of both crack width and rebar existence determined the decrease of this objective function. In that case, the rebar presence retained the diffusion process.

The conclusion of this study is based on results of experimental data and on considered parameters. It is possible that the accuracy of these results would be higher if more experimental results would be available.

ACKNOWLEDGEMENTS

This work is partially supported by the strategic grant POSDRU/159/1.5/S/137516 (2014) of the Ministry of National Education, Romania, co-financed by the European Social Fund- Investing in People, within the Sectoral Operational Programme Human Resources Development 2007-2013. The experimental part is realised at Magneil Laboratory in Ghent, Belgium, within the framework of a Bilateral Scientific Agreement between UGent, Belgium, and UPT, Romania.

REFERENCES

- Yoon, I.S. et al., *Long/short term experimental study on chloride penetration in cracked concrete*, Key Engineering Materials, vol.417-418, pp.765-768 (2010).
- Schlangen, E. et al., *Measurement of chloride ingress in cracked concrete*, in Audenaert K., Marsavina L., De Schutter G. (eds), Int. RILEM workshop on transport mechanisms in cracked concrete, Acco, Leuven, pp.19-25, (2007).
- Ye, H. et al., *Influence of cracking on chloride diffusivity and moisture influential depth in concrete subjected to simulated environmental conditions*, Construction and Building Materials, vol.47, pp.66-79 (2013).
- Aldea, C.M. et al., *Effect of cracking on water and chloride permeability of concrete*, J of Materials in Civil Engineering, ASCE, vol.11(3), pp.181-187 (1999).
- Jang, S.Y. et al., *Effect of crack width on chloride diffusion coefficients of concrete by steady-state migration tests*, Cement and Concrete Research, vol.41(1), pp.9-19 (2011).
- Ismail, M. et al., *Effect of crack opening on the local diffusion of chloride in inert materials*, Cement and Concrete Research, vol.34(4), pp.711-716 (2004).
- Marsavina, L. et al., *Experimental and numerical determination of the chloride penetration in cracked concrete*, Construction and Building Materials, vol.23(1), pp.264-274 (2009).
- Audenaert, K. et al., *Influence of cracks on the service life of concrete structures in a marine environment*, Key Engineering Materials, vol.339, pp.153-160 (2009).
- Pour-Ghaz, M. et al., *Numerical and experimental assessment of unsaturated fluid transport in saw-cut (notched) concrete elements*, ACI Special Publication SP266-06, vol.266, pp.73-86 (2009).
- Sosdean, C et al., *Influence of real cracks on chloride diffusion*, Ysesm Proc. of XIII Youth Symposium on Experimental Solid Mechanics, ed D. Kytyr, CTUP, CZ, 2014, pp.16-120.
- Kwon, S.J. et al., *Service life prediction of concrete wharves with early-aged crack: Probabilistic approach for chloride diffusion*, Structural Safety, vol.31, pp.75-83 (2009).
- Ye, H. et al., *Model of chloride penetration into cracked concrete subject to drying-wetting cycles*, Construction and Building Materials, vol.36, pp.259-269 (2012).
- Capseele, R. et al., *Structural reliability of concrete slabs considering tensile membrane action*, Safety, Reliability and Risk Analysis: Beyond the Horizon, Proceedings, pp.2713-2720 (2013).
- Gouverneur, D. et al., *Experimental investigation of the load-displacement behavior under catenary action in a restrained reinforced concrete slab strip*, Engng. Structures, vol.49, pp.1007-1016 (2013).

15. NT BUILD 492. Concrete, Mortar and Cement-Based Repair Materials: Chloride Migration Coefficient from Non-steady-state Migration Experiments. NORDTEST, 1999.
16. Otsuki, N. et al., *Evaluation of AgNO₃ solution spray method for measurement of chloride penetration into hardened cementitious matrix materials*, ACI Materials Journal, 89 (6), pp. 587-592 (1992).
17. Ožbolt, J., Balabanic, G., Periškić, Kušter, M., *Modelling the effect of damage on transport processes in concrete*, Construction and Building Materials, vol.24(9), pp.1638-1648 (2010).
18. ACI Committee 224. Control of cracking in concrete structures (ACI 224R-90), ACI Manual of Concrete Practice, Part 3, ACI (1999).
19. British Standards Institution. ENV 1991-1-1, BSI, London (1992).
20. British Standards Institution. BS 8110:Part 1, BSI, London (1997).
21. Gérard, B., Marchand, J., *Influence of cracking on the diffusion properties of cement-based materials: Part I: Influence of continuous cracks on the steady-state regime*. Cement and Concrete Research, vol.30(1), pp.37-43 (2000).
22. Li, C.Q., *Initiation of chloride-induced reinforcement corrosion in concrete structural members-experimentation*, ACI Structural Journal, vol.98(4), pp.502-510 (2001).
23. Rodriguez, O.G., Hooton, R.D., *Influence of cracks on chloride ingress into concrete*, ACI Materials Journal, vol.100(2), pp.102-126 (2003).
24. Marsavina, L., Audenaert, K., De Schutter, G., Faur, N., Marsavina, D., *Experimental and numerical determination of the chloride penetration in cracked concrete*, Construction and Building Materials, vol.23(1), pp.264-274 (2009).
25. Subramaniam, K.V., Bi, M., *Investigation of steel corrosion in cracked concrete: Evaluation of macrocell and microcell rates using Tafel polarization response*, Corrosion Science, vol.52, pp.2725-2735 (2010).

ESIS CALENDAR OF CONFERENCES & WORKSHOPS

Event	Date	Location	Contact
2015			
3 rd Int. Conf. on Material and Component Performance under Variable Amplitude Loading (VAL2015)	23-26 March	Prague (Czech Republic)	www.val-conf.org
2 nd Int. Conf. on Damage Mechanics (ICDM2)	8-10 July	University of Technology of Troyes (France)	http://icdm2.utt.fr/ email: icdm2@utt.fr
6 th Int. Conf. on Mechanics and Materials in Design (M2D'2015)	26-30 July	Ponta Delgada (Azores)	paginas.fe.up.pt/clme/m2d2015/
SMIRT 23 – 23 rd Conference on Structural Mechanics in Reactor Technology International	10-14 August	Manchester	www.smirt23.org
CP 2015 – 5 th International Conference on Crack Paths	16-18 September	Ferrara, Italy	www.structuralintegrity.eu
11 th Conf. Mechatronic Systems and Materials (MCM 2015)	2015	Kaunas (Lithuania)	www.ktu.lt/msm
2016			
ECF21 – 21 st European Conference on Fracture	19-24 June	Catania, Italy	www.structuralintegrity.eu
2017			
ICF14 – Fourteenth International Conference on Fracture	7-13 May	Rhodes, Greece	www.icfweb.org
2018			
ECF22 – 22 nd European Conference on Fracture	26-31 August	Belgrade (Serbia)	