

A PROBABILISTIC APPROACH FOR ESTIMATING CORROSION POSSIBILITY OF REINFORCED CONCRETE STRUCTURE CONSIDERING CRACK DEVELOPMENT

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Abstract

Reinforcement corrosion induced by chloride ingress is one of the major threats of reinforced concrete (RC) structures exposed to chloride attack. The cracks of concrete cover provide additional paths of chloride ingress and facilitate the reinforcement corrosion. Current information regarding the influence of crack development on corrosion possibility is insufficient due to lack of proper analytical approach. On this account, a rapid numerical approach (RNA) is developed in this study to study the chloride ingress of cracked concrete. It could consider the crack development and chloride binding effect. This approach is validated through comparisons with the FEM analysis. Based on this approach, it becomes feasible to estimate the corrosion possibility of cracked RC structures.

Keywords: Chloride content; Crack Development; Rapid numerical approach; Corrosion possibility

1. INTRODUCTION

Reinforcement corrosion induced by chloride ingress is one of the principle threats of reinforced concrete (RC) structures exposed to marine environments. Concrete structures undergo continuous deterioration due to combined environmental and loading actions from concrete mixing, such as thermal- or shrinkage -induced cracking. These cracks provide additional diffusion path of chloride ingress and facilitate the reinforcement corrosion [1-5]. On the other hand, the microstructure of cement matrix become denser because of continuous hydration [6, 7]. The cement matrix also chemically absorbs free chloride as Friedel's salt and bound chloride of the diffuse layer of calcium-silicate-hydrate (C-S-H) gel [8, 9]. These two effects enhance the chloride resistance of concrete and suppresses the corrosion possibility of RC structures. Considerable efforts have been made to study these two effects during last decades [1-5, 8, 9]. However, there is little information regarding the influence of cracks and

chloride binding on the corrosion failure time of RC structures. More importantly, chloride ingress of concrete structure involves a lot of uncertainties and randomness, which arise from the variability of material properties (e.g. the diffusion coefficient); the variability of structure geometry (e.g. concrete cover) and the random nature of the marine environment (e.g. the surface chloride content). It is therefore more reasonable to adopt a probabilistic approach to estimate the corrosion failure time of RC structures. Finite element method (FEM) is a possible way to solve these problems. However, probabilistic analysis usually needs millions of samples (e.g. Monte Carlo simulation) to obtain convergent results, which makes the FEM is actually inapplicable. Engineering practices therefore demand a method to optimize design method and maintenance strategy of RC structures. An explicit diffusion solution of two-layer material had been developed in previous study [5, 10]. Based on this two-layer diffusion solution, this study presents a rapid numerical approach (RNA) for estimating the corrosion possibility of cracked RC structures. This approach could consider the crack development and chloride binding effect. This approach is validated through comparisons with the FEM analysis. A case study of an actual structure will be presented in the end of this paper.

2. EXPLICIT DIFFUSION SOLUTION OF TWO-LAYER MATERIAL

Figure 1 shows the diffusion model in a two-layer material. The thicknesses of first layer and second layer are h_1 and h_2 , respectively, and their diffusion coefficients are $D_{t_0,1}$ and $D_{t_0,2}$ at age of t_0 , respectively.

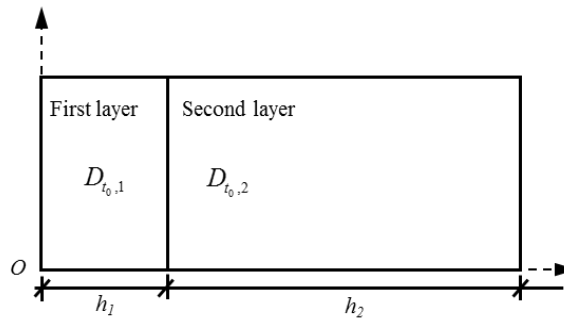


Figure 1: Diffusion model of two-layer material

$$\frac{\partial C(x,T)}{\partial T} = D_{t_0,1} \frac{\partial^2 C(x,T)}{\partial x^2} \text{ for } 0 \leq x \leq h_1 \quad (1)$$

$$\frac{\partial C(x,T)}{\partial T} = D_{t_0,2} \frac{\partial^2 C(x,T)}{\partial x^2} \text{ for } h_1 \leq x \leq h_1 + h_2 \quad (2)$$

where $C(x,T)$ is the chloride profile; x is the interested concrete depth; and T is the interested exposure time.

An explicit solution for two-layer material was developed in previous study [5, 10].

$$C(x,T) = C_T^{x=0} + \sum_{n=1}^{\infty} A'_n f_n(x, \lambda_n) \exp(-\lambda_n^2 T) \quad (3)$$

where $C_T^{x=0}$ is the surface chloride content; and $f_n(x, \lambda_n)$ is defined as

$$f_n(x, \lambda_n) = \begin{cases} \frac{\cot(\lambda_n h_2 / \sqrt{D_{t_0,2}})}{\sin(\lambda_n h_1 / \sqrt{D_{t_0,1}})} \sin(\lambda_n x / \sqrt{D_{t_0,1}}) & 0 \leq x \leq h_1 \\ \frac{1}{\sin(\lambda_n h_2 / \sqrt{D_{t_0,2}})} \cos[\lambda_n (x - h_1 - h_2) / \sqrt{D_{t_0,2}}] & h_1 \leq x < h_1 + h_2 \end{cases} \quad (4)$$

A'_n is determined by Eq. (5)

$$A'_n = \int_0^{h_1+h_2} [\bar{C}(x) - C_T^{x=0}] f_n(x, \lambda_n) dx / \int_0^{h_1+h_2} f_n^2(x, \lambda_n) dx \quad (5)$$

where $\bar{C}(x)$ is the exited chloride content; and

$$\int_0^{h_1+h_2} f_n^2(x, \lambda_n) dx = \frac{\cot^2(\lambda_n h_2 / \sqrt{D_{t_0,2}})}{2 \sin^2(\lambda_n h_1 / \sqrt{D_{t_0,1}})} \left[h_1 - \frac{\sqrt{D_{t_0,1}}}{2 \lambda_n} \sin\left(\frac{2 \lambda_n h_1}{\sqrt{D_{t_0,1}}}\right) \right] + \frac{1}{2 \sin^2(\lambda_n h_2 / \sqrt{D_{t_0,2}})} \left[h_2 + \frac{\sqrt{D_{t_0,2}}}{2 \lambda_n} \sin\left(\frac{2 \lambda_n h_2}{\sqrt{D_{t_0,2}}}\right) \right] \quad (6)$$

Characteristic roots λ_n are determined by Eq. (7)

$$\tan(\lambda_n h_1 / \sqrt{D_{t_0,1}}) \tan(\lambda_n h_2 / \sqrt{D_{t_0,2}}) = \sqrt{D_{t_0,1} / D_{t_0,2}} \quad (7)$$

3. RAPID NUMERICAL APPROACH FOR CRACK DEVELOPMENT, CHLORIDE BIDDING AND

3.1 Simulation approach of crack development

The concrete cover always cracks due to combined loading and environmental actions. These cracks facilitates the chloride ingress by two effects : (1) developing crack length (e.g. Figure 2 (a)) ; and (2) increasing diffusion coefficient of cracked concrete (e.g. D_I in Figure 2 (b)).

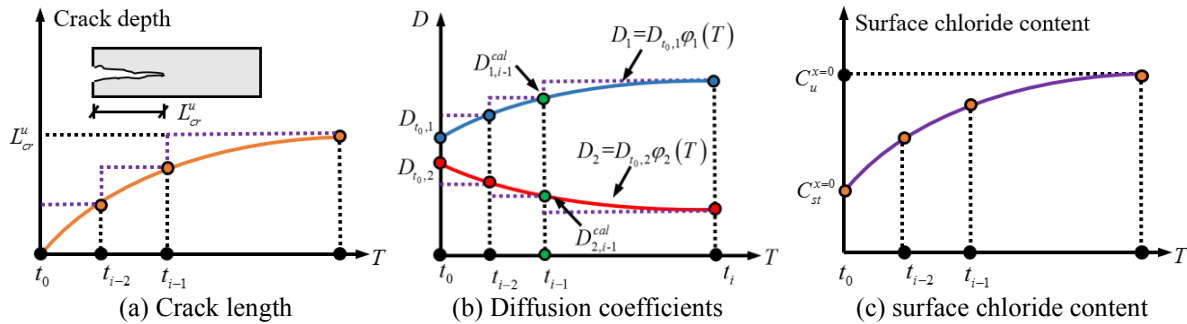


Figure 2: Crack development model and simulation approach

To simulate these two effects, a feasible and practical way is to approach the crack length development and increasing diffusion coefficients with the step functions, as shown in Figure 2 (b). Since the crack length and chloride diffusion coefficient are approximated as a constant

in each step, the analytical solution is approached to accurate result as the number of steps increases.

3.2 Simulation approach of time-dependency of uncracked concrete

As mentioned previously, the porosity and chloride diffusion coefficient of uncracked concrete decreases as cement hydration proceeds. The diffusion properties of uncracked concrete shows opposite trend of cracked concrete. This effect should be considered. Because the time-dependency of crack length and diffusion coefficient of cracked concrete are simulated by step functions, the same approach can be used for uncracked concrete as well (e.g. D_2 in Figure 2 (b)).

3.3 Simulation approach of time-dependency of surface chloride content

Considerable researches reported that the surface chloride content is time-dependent as well. Like the crack length and chloride diffusion coefficient, the surface chloride content is approximately represented with the step function with the same time steps, as shown in Figure 2 (c).

3.4 Simplified chloride binding model

Liu et al. [11] proposed a simplified model for chloride binding effect. They assumed the the variation of total chloride C_t along depth is same as the variation of free chloride C_f . Therefore, the chloride binding effect can be considered by an apparent diffusion coefficient (i.e. Eq. (8))

$$D^* = \frac{D}{1 + \partial C_b / \partial C_f} \quad (8)$$

where C_b is bound chloride. Liu et al. [11] further assumed that the binding ratio ϕ is constant (i.e. Eq. (9)) when the free chloride concentration is not high

$$\partial C_b / \partial C_f = \phi \quad (9)$$

Thus, the apparent diffusion coefficient can be determined by Eq. (10)

$$D^* = D / (1 + \phi) \quad (10)$$

4. VALIDATION OF THE PROPOSED NUMERICAL APPROACH

To validate this rapid numerical approach (RNA) for predicating the chloride ingress for cracked concrete, 4 case studies were carried out in this study. The time-dependency of cracked concrete and uncracked concrete are described by power functions (Eqs. (11) and (12)). The surface chloride content is described by Eq. (13). The crack developments are described by 10 points step function (e.g. Figure 3 (b)). All values of the parameters used in the analyses are summarized in Table 1.

$$D_1 = D_{t_0,1} \left(\frac{t_{st} + T}{t_0} \right)^{-\alpha_1} \quad (11)$$

$$D_2 = D_{t_0,2} \left(\frac{t_{st} + T}{t_0} \right)^{-\alpha_2} \quad (12)$$

$$C_T^{x=0} = C_{st}^{x=0} + C_u^{x=0} (1 - e^{-\beta T}) \quad (13)$$

where $D_{t_0,1}$ and $D_{t_0,2}$ are the chloride diffusion coefficient of the cracked and uncracked concrete at age t_0 ; α_1 and α_2 are the time-dependent coefficients of cracked and uncracked concrete; t_0 is the curing age of specimens, t_{st} and t_{ex} are the initial and final exposure times; and $C_{st}^{x=0}$ is the initial surface chloride content, $C_u^{x=0}$ is the ultimate surface chloride content, and β is the ageing factor of the surface chloride content.

Table 1: Values of parameters used for validation of RNA.

Case	L_{cr}^u (mm)	$D_{t_0,1}$ (mm ² /d)	$D_{t_0,2}$ (mm ² /d)	$C_{st}^{x=0}$ (%)	$C_u^{x=0}$ (%)	α_1	α_2	β	ϕ	t_0 (d)	t_{st} (d)	t_{ex} (year)
C1	8.0	2.5×10^{-2}	2.5×10^{-2}	2.0	3.5	-0.20	0.25	0.25	0.15	120	180	30
C2	8.0	2.0×10^{-2}	2.0×10^{-2}	2.0	3.5	-0.15	0.20	0.20	0.18	100	180	40
C3	8.0	2.0×10^{-2}	2.0×10^{-2}	1.5	3.5	-0.20	0.20	0.15	0.18	90	180	50
C4	8.8	2.0×10^{-2}	2.0×10^{-2}	1.5	3.5	-0.20	0.20	0.15	0.18	90	180	50

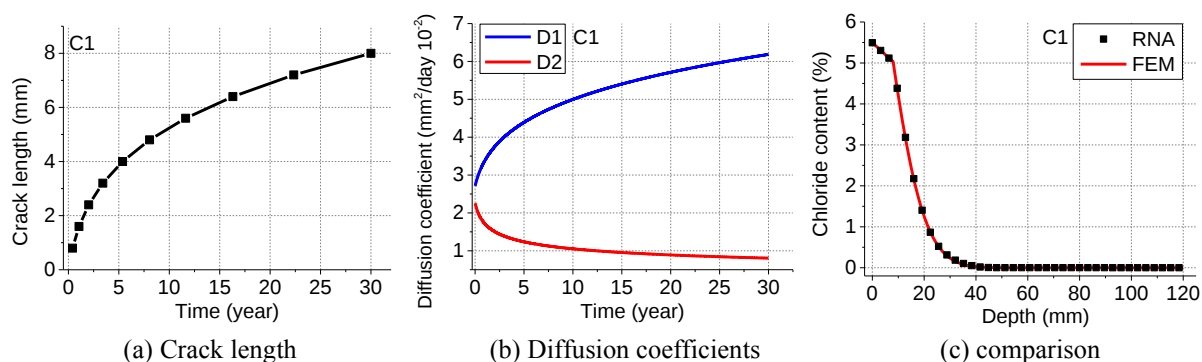


Figure 3: Verification of simple case C1

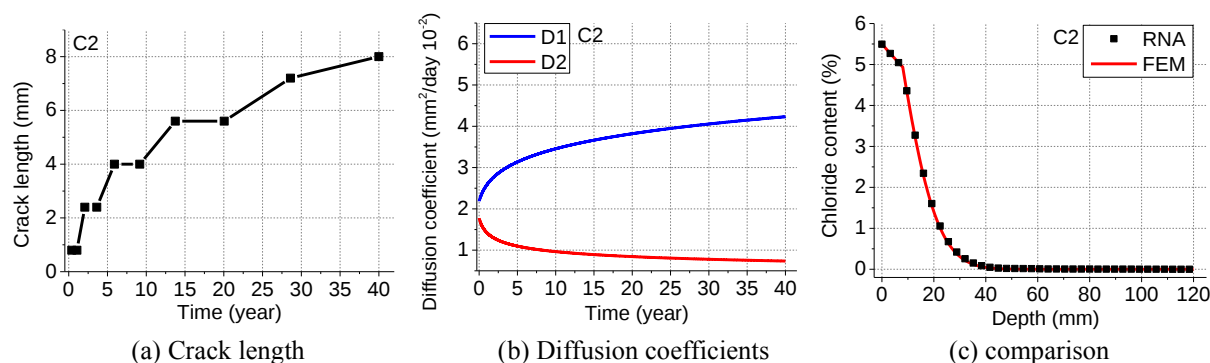


Figure 4: Verification of simple case C2

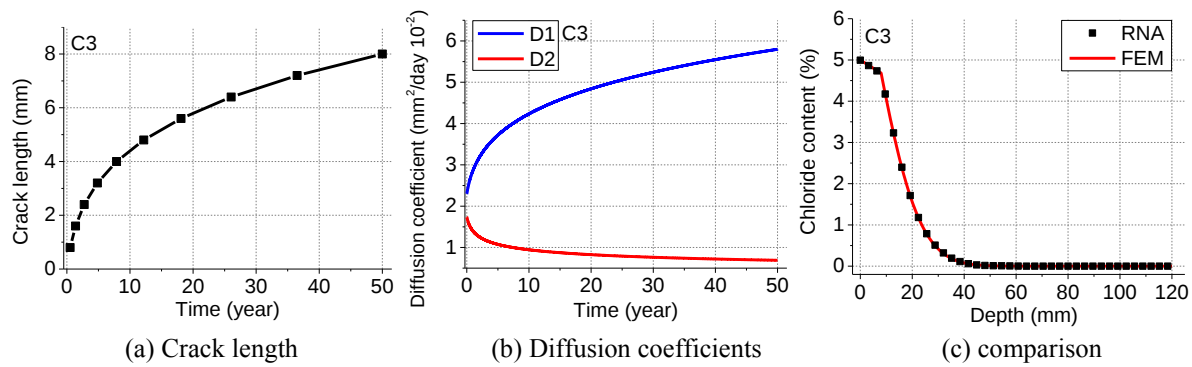


Figure 5: Verification of simple case C3

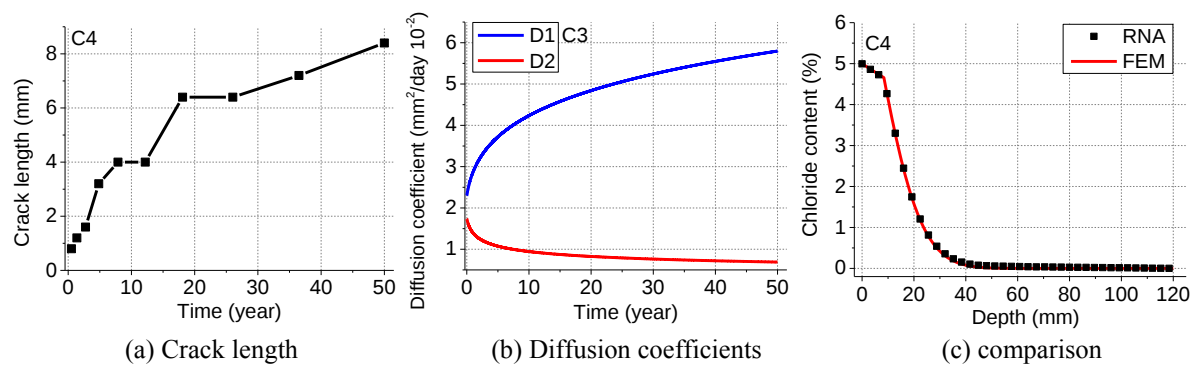


Figure 6: Verification of simple case C4

The crack length development of these four cases are shown in Figure 3~6 (a). The time-dependencies of diffusion coefficient are shown in Figure 3~6 (b). Both are simulated by 10 steps. The analytical prediction is compared with the FEM [24], where the element length and the time step are 0.4 mm and 0.1 day, respectively. Figure 3~6 (c) shows the comparisons between the result of RNA and FEM. The number of characteristic root and the interval of depth is 10 and 0.4 mm, respectively. A perfect agreement is presented between them, which validate the reliability of the proposed numerical approach. The computation times of RNA and FEM are shown in Table 2. The computation time enormously decreases (e.g. almost one-hundred thousand times in case C4). It makes the probabilistic estimation of corrosion failure time of RC structures feasible.

Table 2: Comparison of computation time for FEM and RNA.

Time (s)	C1	C2	C3	C4
FEM	8602	20099	23702	23689
RNA	0.2543	0.2651	0.2475	0.2567
Comparison	3.38×10^4	7.58×10^4	9.58×10^4	9.23×10^4

5. A CASE STUDY OF AN ACTUAL CONCRETE STRUCTURES

A case study of an actual port is conducted to show the application of RNA on predicting the corrosion possibility of cracked RC structure. This port structure is located at Shenzhen City, Mainland China and exposed to a severe marine environment. The concrete cover depths were extensively measured and the statistical information is shown in Figure 7 (a). The

parameters used for simulation are summarized in Table 3. The effects of the chloride binding effect and crack development are investigated. The number of time steps and characteristic roots are both 10. The interval of depth is 1 mm. The sample size of Monte-Carlo simulation is two million and the calculation were completed in 12 hours.

Figure 7 are analysis results of corrosion possibility of cracked concrete structures. Figure 7 (b) studies the influence of crack development on the corrosion possibility. The crack length increases $L_{cr}^u/10$ every ten year (L_{cr}^u is the ultimate crack length). The corrosion possibility increases as the ultimate crack length L_{cr}^u increases and degradation ratio of diffusion coefficient α_1 increases. Comparing to the ultimate crack length, the degradation ratio of diffusion coefficient has more significant effect on the corrosion possibility. Figure 7 (c) shows the chloride binding effect. The corrosion possibility decreases as the chloride binding effect increases. It shows that chloride binding effect cannot be ignored. It should be noted that the chloride binding effect is considered by a simplified model in this study. More accurate model should be developed in the future to study the chloride binding effect. In conclusion, this proposed rapid numerical approach can be used to study the corrosion possibility of cracked RC structures.

Table 3: Parameters for Monte Carlo simulation.

Parameter	Mean	COV	Distribution
Ultimate crack length (mm)	0, 10, 20	0.10	Lognormal distribution
Concrete cover (mm)	61.49mm	0.17	Normal distribution
Binding ratio ϕ	0, 0.10, 0.15	0.10	Normal distribution
$D_{t_0,1}$ (mm ² /day)	0.20	0.20	Normal distribution
$D_{t_0,2}$ (mm ² /day)	0.20	0.20	Normal distribution
α_1	-0.25	0.20	Normal distribution
α_2	0.2	0.20	Normal distribution

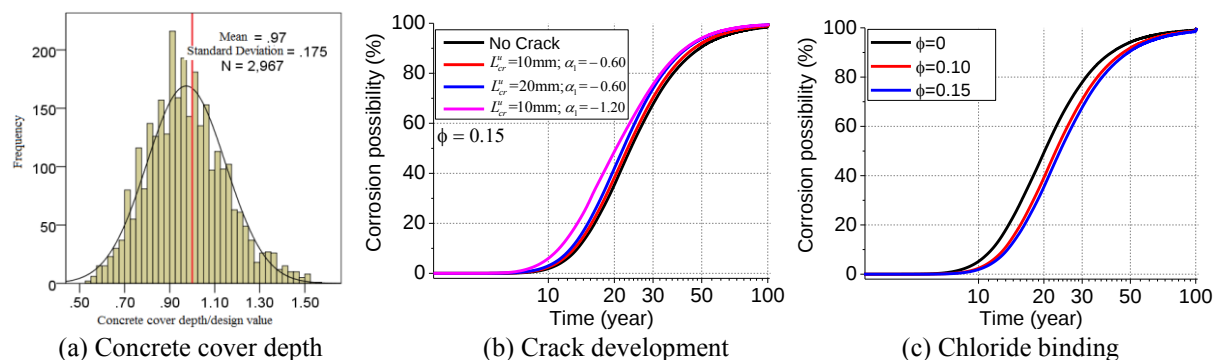


Figure 7: Corrosion possibility of concrete port

6. CONCLUSION

A rapid numerical approach is developed for the chloride diffusion of cracked concrete. In this approach, the crack development and chloride binding ratio are both taken into account. Based on numerical results, it has been confirmed that the RNA is in excellent agreement with

the FEM for simple and complicated cases. More importantly, the RNA can improve the computational efficiency enormously. With the RNA, the Monte-Carlo simulation can be implemented to estimate the corrosion possibility of cracked RC structures in marine environments. The analysis results show the crack development and chloride binding both have significant influence on the corrosion possibility.

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REFERENCES

- [1] Prezzi M., P.J Geyskens and P. Monteiro, "Reliability approach to service life prediction of concrete exposed to marine environments", *ACI Mater.* 93(6) (1996) 544-552.
- [2] Saad, A. "Effectiveness of concrete surface treatment materials in reducing chloride-induced reinforcement corrosion", *Constr Build Mater.* 1997, 11(7-8): 443-451.
- [3] Val D.V. and Trapper P.A. "Probabilistic evaluation of initiation time of chloride-induced corrosion", *Reliab Eng Syst Safe.* 93(3) (2008) 364-372.
- [4] Bertolini L., Elsener B., Pedersen P., Redaelli E. and Polder R.B, "Corrosion of steel in concrete: Prevention, diagnosis, repair", John Wiley & Sons, 2013.
- [5] Dai J. and Wang T. "Probabilistic model for service life prediction of water repellent rc structures in marine environments", Proceeding of the 7th Asia Pacific Young Researchers and Graduates Symposium Malaysia, 2015.
- [6] Pack, S.W., Jung M.S., Song H.W., Kim S.H., Ann K.Y. "Prediction of time dependent chloride transport in concrete structures exposed to a marine environment", *Cem. Concr. Res.* 40(2) (2010) 302-312.
- [7] Maekawa K., Ishida T., Kishi T. "Multi-scale modeling of structural concrete", CRC Press, 2008.
- [8] Tang L.P. and Nilsson L.O., "Chloride binding capacity and binding isotherms of opc pastes and mortars", *Cem. Concr. Res.* 23(2) (1993) 247-253.
- [9] Shi Z., Geiker M.R., De Weerd K., Østnor T.A., Lothenbach B., Winnefeld F. and Skibsted J. "Role of calcium on chloride binding in hydrated portland cement–metakaolin–limestone blends", *Cem. Concr. Res.* 95 (2017) 205-216.
- [10] Wang T., Zheng J., Ishida T. and Dai J. "A rapid numerical approach for time-dependent chloride diffusion in surface-treated concrete", *Cem. Concr. Comp.*(submitting).
- [11] Liu J., Xing F., Dong B.Q., Ma H.Y. and Pan D. "New equation for description of chloride ions diffusion in concrete under shallow immersion condition", *Mater. Res. Innovat.* 18(sup2) (2014) S2-265-S262-269.