Repair of concrete structures in marine environment: optimization of concrete removing and cover

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REPAIR OF CONCRETE STRUCTURES IN MARINE ENVIRONMENT: OPTIMIZATION OF CONCRETE REMOVING AND COVER

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ABSTRACT

The first part of this paper presents a sensitivity analysis of a comprehensive chloride ingress model. The sensitivity study is used to identify the more influencing environmental and model parameters. In a second part, the model of chloride ingress is adapted to model maintenance by cover rebuilding. This model allows us to study the effect of three parameters: quality of the repair material, repair depth and repair interval. From this study, it is concluded that there are optimum values that minimize both material costs and environmental impact.

INTRODUCTION

For reinforced concrete (RC) structures, corrosion induced by chloride ingress generates important damage after 10 or 20 years of service (Rosquoët *et al.*, 2006, Bonnet *et al.*, 2007). Consequently, its inspection and maintenance are essential to ensure an optimal level of serviceability and safety during its lifespan. It is shown over the word that maintaining safety requirements increases agency costs. Therefore, the main objective of this paper is to determine the parameters to be taken into account for increasing the effectiveness of repair by "cover rebuilding".

Recently only few studies (Bastidas-Arteaga *et al.*, 2010a and 2010b) provide comprehensive models for modeling chloride ingress under realistic conditions. Section 2 presents the basic principles of this model. Due to the complex phenomena involved in chloride ingress, several parameters should be quantified. A deterministic sensitivity analysis of the parameters influencing chloride ingress is presented in Section 3. Section 4 focuses on the effect of the parameters influencing the effectiveness of "cover rebuilding".

DESCRIPTION OF THE REPAIR TECHNIQUE AND THE CHLORIDE INGRESS MODEL

Cover rebuilding

The requirements for this technique were defined within the framework of the MAREO[1] project with the collaboration of public agencies, construction companies and research institutions. In the strategy of maintenance considered herein, "cover rebuilding", repair is undertaken by rebuilding the chloride-polluted concrete cover by several techniques (wet shotcrete, dry shotcrete, formed concrete and manual repair, Figure 1). Cover rebuilding is applicable to large-scale repair projects and is currently being tested on real RC structures at the Atlantic Port of Nantes St Nazaire.

[1] Maintenance and REpair of concrete coastal structures: risk-based Optimization (MAREO) Project

(a) Beam after hydrodemolition (b) Repair of beams by shotcrete

Figure 1. Description of the repair procedure

Chloride ingress model

Chloride ingress into concrete is controlled by a complex interaction between physical and chemical mechanisms that have often been modeled as a diffusion phenomenon in saturated media (Fick's second law) (Tuutti, 1982). To properly model this phenomenon, it is implemented a comprehensive model that considers the interaction between: (i) chloride penetration, (ii) diffusion of moisture and (iii) heat transfer (Bastidas-Arteaga *et al.*, 2010b). The coupled phenomenon is described by a set of partial differential equations that is solved by combining finite element and finite difference methods. The description of the formulation of the model is beyond the scope of this paper. We used here a one-dimensional model (semi-infinite domain). According to Bastidas-Arteaga *et al*, (2010b), this phenomenon is mainly governed by *environmental* and *model* parameters.

SENSITIVITY ANALYSIS OF THE CHLORIDE PENETRATION MODEL

Table 1 presents the parameters that should be quantified for modeling chloride penetration. In reliability analysis, their distribution and correlations should also be provided. This point should be considered with care when using analytical, empirical or semi-empirical relationships that have been developed by researchers looking for a good representation of average trends. Even if they have good asymptotic properties, their sensitivity to random inputs should be analyzed and submitted to expert judgment. This section studies the influence of these parameters.

Table 1. Parameters of the chloride penetration model

Phenomena	Parameter	Symbol	Units
Chloride ingress	Reference chloride diffusion coefficient (apparent)	$D_{c,ref}$	m^2/s
	Activation energy of the chloride diffusion process	U_c	kJ/mol
	Aging factor	m	
Humidity diffusion	Reference humidity diffusion coefficient	$D_{h,ref}$	m^2/s
	Parameter representing the ratio $D_{h,min}/D_{h,max}$	α_0	
	Parameter characterizing the spread of the drop in	n	
	Activation energy of the chloride diffusion process	U	kJ/mol
Heat transfer	Thermal conductivity of concrete	λ	W/(m°C)
	Specific heat capacity of concrete	c_q	J/(kg°C)
	Density of concrete	ρ_c	kg/m^3

Sensitivity to environmental actions

In the following the environmental chloride concentration is constant and equals 6 kg/m^3. We consider two assumptions for modelling humidity h and temperature T as functions of time. In the former, h and T are constant with time –i.e., T_{mean}=12.5 ºC and h_{mean}=0.75. In the latter, h and T are cyclic and modelled by a sinusoidal function that varies with time (one year periodic) with: T_{min}=-5 ºC, T_{max}=30 ºC, h_{min}= 0.6 and h_{max}= 0.9. To analyze the effect of temperature and humidity, we study the following situations:

– **CCC**: the input models are constant for temperature, humidity and environmental chloride concentration.

– **SCC**: the input models are sinusoidal for temperature and constant for humidity and environmental chloride concentration.

– **CSC**: the input models are constant for temperature and environmental chloride concentration and sinusoidal for humidity.

– **SSC**: the input models are sinusoidal for humidity and temperature and constant for environmental chloride concentration.

Figure 2 presents the chloride profiles after 38 years of exposure for the above mentioned cases. It appears clearly that the most critical case is SSC when both temperature and humidity are time-variant. Note that when humidity is constant (cases CCC and SCC) only diffusion occurs and the profiles are very similar whatever temperature model.

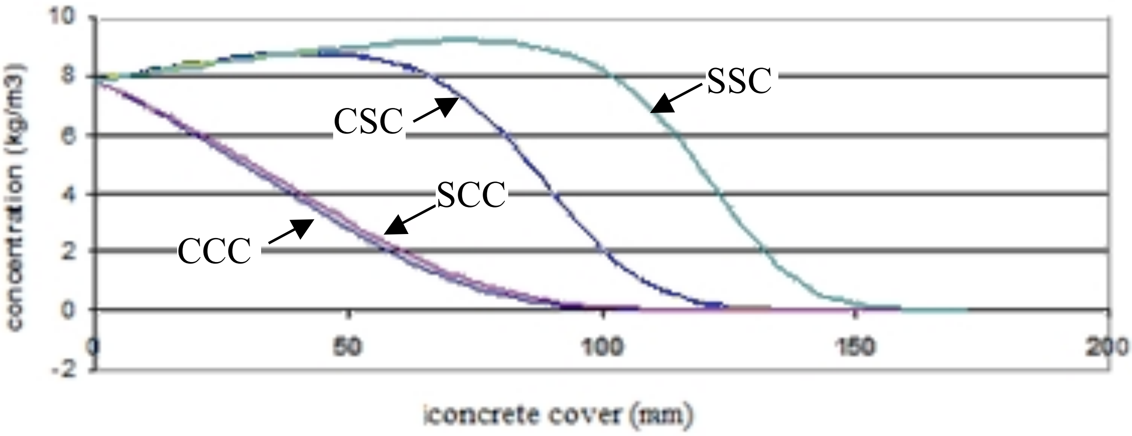


Figure 2. Profiles of chlorides after 38 years

Sensitivity to the model parameters

Table 2 presents the representative values (minimum, mean and maximum) selected for this analysis. Each sensitivity analysis is performed independently. It means that when we study the sensitivity of one parameter the other 9 parameters are fixed at its mean values. Moreover, the four environmental assumptions described in section 3.1 as well as three concrete covers: 30, 50 and 70 mm, are considered. Consequently, 360 cases for a time-window of 100 years have been computed and studied.

Table 2. Values selected for the model parameters of the chloride penetration model

Parameter	Units	Min	Mean	Max
$D_{c,ref}$ (apparent)	m^2/s	1.80E^{-11}	3.00E^{-11}	4.20E^{-11}
U_c/R	ºK	3800	4600	5400
m		0	0.15	1
$D_{h,ref}$	m^2/s	1.80E^{-10}	3.00E^{-10}	4.20E^{-10}
α_0		0.025	0.05	0.1
n		6	10	16
U/R	ºK	2700	3000	4700
λ	W/(m°C)	1,4	2,4	3,6
c_q	J/(kg°C)	840	900	1170
ρ_c	kg/m^3	2200	2400	2600

Table 3 presents the most relevant results of this sensitivity study according to the following the classification:
– S00: low sensitivity with time and depth.
– S01: low sensitivity with time but significant sensitivity with depth.
– S10: significant sensitivity with time but low sensitivity with depth.
– S11: significant sensitivity with time and depth.

Based on this classification, dark grey cells indicate the most influent parameters, clear grey cells show the parameters with medium influence and white cells the parameters with low influence. It is shown that chloride ingress is very sensitive to chloride and humidity diffusion coefficients.

Table 3. Sensitivities of model parameters for the environmental models

Parameter	CCC	CSC	SCC	SSC
$D_{c,ref}$ (apparent)	S11	S11	S11	S11
U_c/R	S10	S10	S10	S10
m	S10	S01	S10	S11
$D_{h,ref}$	S11	S11	S10	S11
α_0	S11	S11	S01	S01
n	S00	S00	S00	S00
U/R	S10	S10	S10	S10
λ	S10	S10	S11	S10
c_q	S00	S00	S00	S00
ρ_c	S00	S00	S00	S00

SIMULATION OF MAINTENANCE

Since testing the performance of the repair technique under several conditions is expensive and time-consuming, we adapted the numerical model of chloride penetration presented in section 2 to simulate the effects of repair. Three factors are considered to study the effectiveness of the maintenance policy:
– quality of the repair material (Table 4);
– depth of repaired concrete, c_{rem}; and
– repair interval (time between two repairs).

These factors can be considered as parameters of optimization in future works. For this analysis we only consider the most realistic environmental condition SSC. The maintenance model provides the evolution of the total chloride concentration (in kg/m^3 of concrete) at several depths for each studied case. The total critical chloride content C_{crit} is computed by assuming that corrosion starts for a content of 0.5% of cement mass. This value corresponds to the mean between French (0.4%) and Spanish (0.6%) requirements. Thus, for a concrete containing 400 kg of cement per m^3, C_{crit} = 2kg/m^3 of concrete.

Effect of quality of the repair material

The parameters defining the quality of the repair material (Table 4) were determined based on the values presented in Table 2. The results presented in Figure 3 concern a maintenance policy where repair is carried out by removing 6 cm of chloride-contaminated concrete –i.e., c_{rem} = 6cm. The evolution of chloride content at depths of 5 and 7 cm are presented herein. We can observe that, depending on the quality of the repair material, the factor between the chloride content after 100 years reaches 10. When considering a critical chloride content of 2 kg/m^3 at a cover thickness of 5 cm, the low quality material needs probably a repair action every 4 years (not reasonable from cost point of view). In contrast, for high quality materials, repairs carried out every 25 years are probably sufficient.

Table 4. Material parameters for the considered qualities

Parameter	Units	High quality	Medium quality	Low quality
$D_{c,ref}$ (apparent)	m^2/s	1.80E-11	3.00E-11	4.20E-11
U_c/R	ºK	5400	4600	3800
m		0.15	0.15	0.15
$D_{h,ref}$	m^2/s	1.80E-10	3.00E-10	4.20E-10
α_0		0.025	0.05	0.1
n		16	10	6
U/R	ºK	4700	3000	2700
λ	W/(m°C)	3.6	2.4	1.4
c_q	J/(kg°C)	900	900	900
ρ_c	kg/m^3	2400	2400	2400

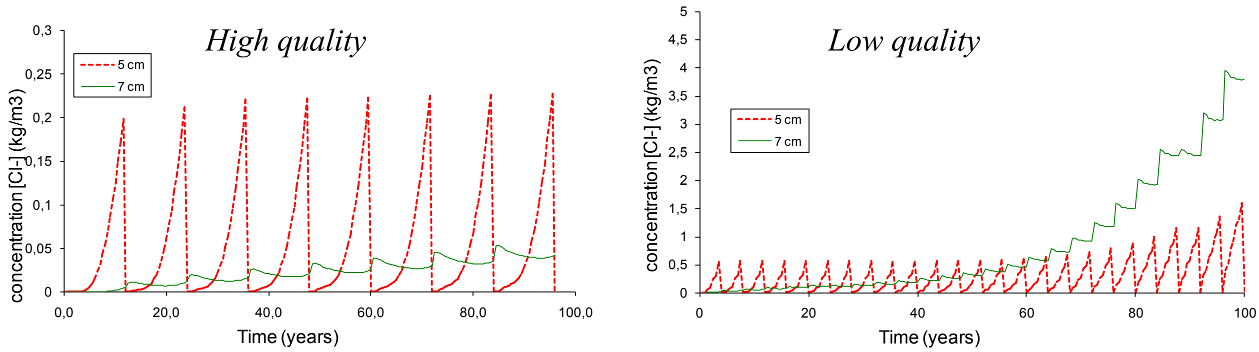
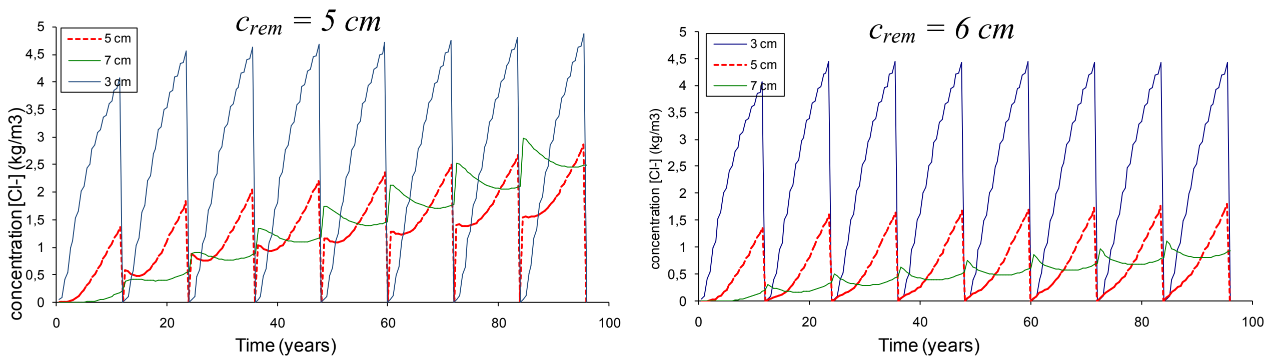


Figure 3. Effect of the quality of the repair material on the evolution of chloride with time

<u>Effect of repair depth</u>

Since there are several cases to analyze, we focus here on the SSC case and the medium quality material. Let us consider the effect of three depths: c_{rem} = 5, 6 and 7 cm and a repair interval of 12 years. Figure 4 presents the effect of depth of repaired concrete on the evolution of the chloride content at 3, 5 and 7 cm. It is shown in all the cases that the chloride content at 7 cm decreases immediately after repair and increases when the chloride ions ingress into the repaired concrete. It means that chloride content at this position moves into two directions inside the structure and towards the concrete surface. When considering a critical chloride content of 2 kg/m^3 at 5 cm and a life-cycle of 100 years, the removing of 6 cm seems to be optimal from economical and environmental point of view (reduction of waste and CO_2 emissions).



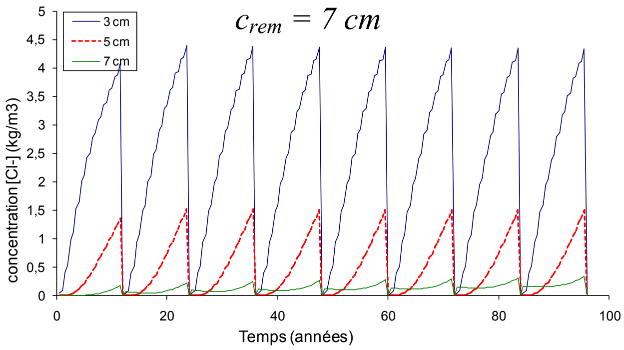


Figure 4. Effect of c_{rem} on the chloride content

Effect of repair interval

In order to study the effect of the length of the repair interval, t_r, we consider a medium quality material and c_{rem} = 6 cm. Figure 5 illustrates the evolution of chloride content at 3, 5 and 7 cm for three repair intervals. The overall behavior indicates that the chloride concentrations at 5 and 7 cm decrease for lower t_r. By taking a critical chloride content of 2 kg/m^3 at 5 cm and a reference period of 100 years, it is observed that a repair interval of about 12 years seems to be optimal. However, a comprehensive maintenance policy should consider time-variant repair intervals to optimize the management of resources and minimize the probability of corrosion initiation.

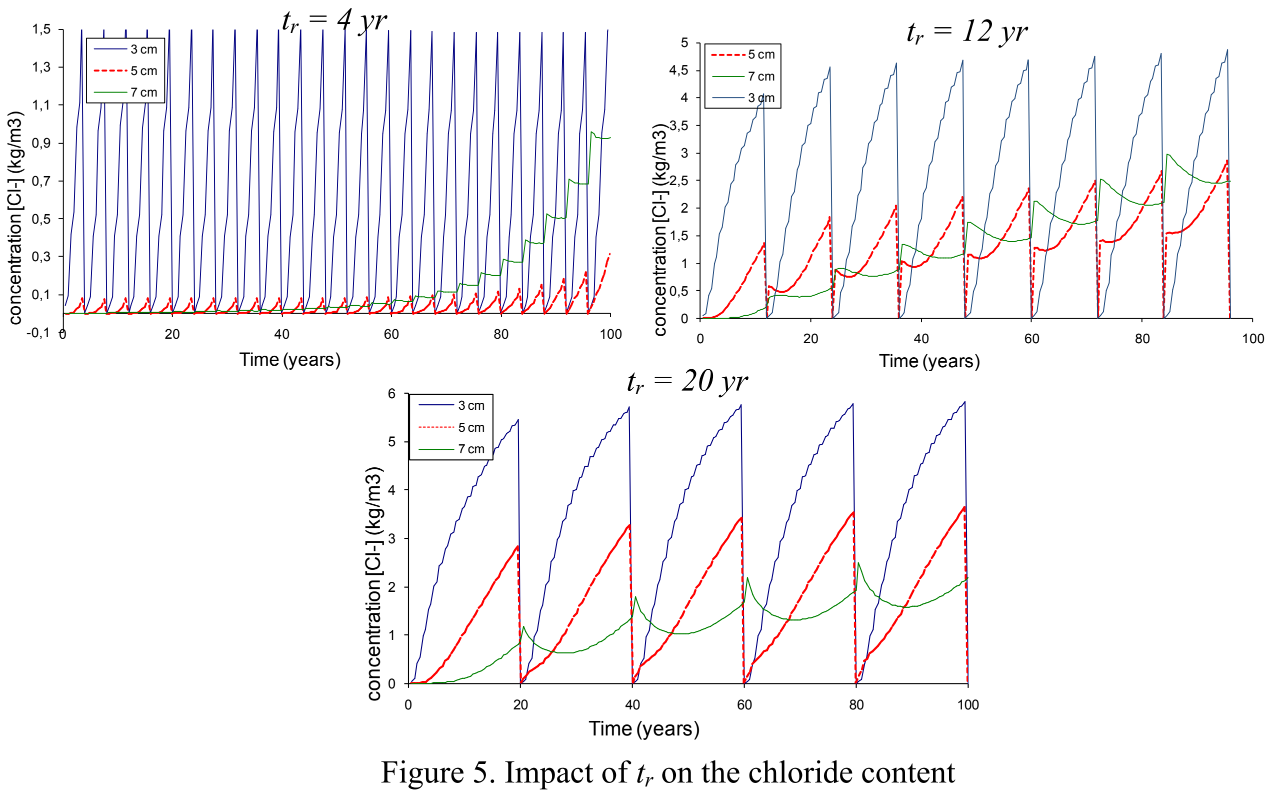


Figure 5. Impact of t_r on the chloride content

CONCLUSIONS

The first part of this paper presented a sensitivity analysis of the chloride penetration model. This analysis showed that chloride ingress is highly influenced by the cyclic variation of temperature and humidity. After, we identified the most influencing parameters of the model. The second part illustrates the effects of the three parameters that control the effectiveness of cover rebuilding: quality of the repair material, repair depth and repair interval. The results of this analysis show that there are optimum values of these parameters that minimize both material costs and environmental impact.

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