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Probabilistic approach for durability design of reinforced concrete in marine environment

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ABSTRACT

A probabilistic approach to durability is proposed for the design of reinforced cover of a concrete immersed in sea water. It uses a non-linear chloride diffusion model for a saturated medium, which is first exposed with its physical parameters. Parameter variability is estimated and used through the probabilistic approach to assess the probability of reaching a critical chloride concentration near the reinforcement for a given service life. Based on the concrete formulation and the cement chemical composition, the model parameters are evaluated with their associated random distribution. The corrosion risk is then estimated through the Hasofer–Lind reliability index. Currently, the methodology is available for Ordinary Portland Cement (OPC) and for saturated media. A practical application is proposed to underline the applicability of the methodology. The decrease in the reliability index with time is computed for a cover depth coming from actual design rules. The probabilistic sensitivity factors are also assessed and show the importance of some model parameters called "durability indicators".

1. Introduction

Corrosion is the main cause of damage in reinforced concrete structures especially in marine environments where chloride diffusion can produce serious damage. For many years, the notion of durability has been considered to be as fundamental as the mechanical performance but, despite improvements in the understanding of chloride diffusion during recent decades, durability design criteria are still far from perfect [1]. In fact, we observe that there is generally a random variation in the physical properties of concrete due to variability of fabrication on building sites [2]. The actual design of concrete cover is empirical, chosen in function of the structural class and the environment, and its variability is only taken into account with an inclusive term depending on controls in the fabrication process [3]. The aim of this paper is to propose an approach that integrates the composition of concrete and a realistic variability of the physical properties associated with chloride ingress, in order to make an objective and probabilistic prediction of its durability. To this end, we need to combine a diffusion model for chloride and a probabilistic method. First, the diffusion model in a saturated medium will be explained. The associated physical parameters, considered as random variables, are presented and their distribution laws assessed from experiments on OPC. Then the probabilistic method is proposed to evaluate the probability of reaching the critical chloride concentration through the Hasofer–Lind reliability index. A practical application to concrete submerged in sea water is then proposed.

2. Description of the model

A model for predicting chloride ingress into concrete always aims to predict a chloride profile $C(x,t)$. The transport of chlorides into porous cement-based materials can be described through two different types of model: empirical or physical. The first type of models are called empirical because field data are necessary to calibrate them and obtain the parameters needed to predict chloride concentration profiles by using the analytical solution of Fick's second law for a semi-infinite medium. They were almost the only ones available for 20 years, from 1970, when Collepardi [4] proposed the first model, up to around 1990, and these are still widely used in more or less sophisticated forms, e.g. to evaluate the time before corrosion initiation. These models are very simple but were not used in our general probabilistic design methodology because they need calibration on experimental tests for each application.

Recent research and experiments have led to the development of models that fit the physical and chemical phenomena involved in chloride ingress better. A new way to describe chloride ingress, called the multi-species approach, is based on the Nernst–Planck Equation, which describes the diffusion and the ionic interaction between several chemical species [5–7]. These models are the most complete but the greater number of input data required makes the statistical analysis too heavy for the probabilistic methodology. Moreover, although we need accuracy for our prediction, the computation time for multi-species models is not compatible with the probabilistic approach, which calls the model many times.

As our study was limited to concrete immersed in sea water, we decided to use a non-linear model of chloride diffusion in a saturated

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Table 1
OPC concretes mixes [10] for the elementary model of chloride effective diffusion coefficient (with designation adopted by [10] in column 1).

Concrete mix	Cement (kg/m^3)	Aggregates (kg/m^3)	w/c	v_p
1–35	450	1695	0.35	0.36
1–40	420	1692	0.40	0.36
1–50	370	1689	0.50	0.36
1–75	240	1812	0.32	0.32
2–35	450	1695	0.36	0.36
2–40	420	1692	0.40	0.36
2–50	390	1646	0.50	0.36
2–60	310	1737	0.60	0.34
2–75	350	1784	0.75	0.33
7–35	450	1854	0.35	0.30
7–40	420	1851	0.40	0.30
7–75	265	1900	0.75	0.38
8–35	470	1819	0.35	0.31
8–40	440	1813	0.40	0.31
8–50	410	1762	0.50	0.33
8–60	330	1838	0.60	0.30
8–75	270	1886	0.75	0.29
H3	492	1845	0.3	0.30
H9	500	1832	0.3	0.31
Ö	420	1685	0.4	0.36

medium where the chloride penetration can be modelled by Fick's law, which is a good compromise between empirical models and multi-species models [8,9]. The free chloride mass balance equation is then:

$$\frac{\partial c}{\partial t} = D_{app} \cdot \frac{\partial^2 c}{\partial x^2} \quad \text{and} \quad D_{app} = \frac{D_e}{p + (1-p) \cdot \rho_s \cdot \frac{\partial C_b}{\partial c}} \tag{1}$$

In Eq. (1), D_e represents the effective diffusion coefficient (m^2/s), c the free chloride concentration (mol/m^3 of solution) depending on time and depth, C_b the bound chlorides (mol/kg of dry concrete), p the porosity, and ρ_s the absolute density of material (kg/m^3). While an empirical model solves this kind of equation with an analytical solution for a semi-infinite medium and especially with a constant value for $\delta C_b/\delta c$, Eq. (1) is solved using a semi-implicit numerical scheme of finite differences which allows the shape of the binding isotherm $C_b(c)$ to be taken into account.

In this methodology, and for simplicity of use, only the composition of the concrete, the chemical composition of the cement and the measurement of water porosity are necessary. Two elementary models are firstly proposed to estimate the chloride effective diffusion coefficient D_e and the chloride binding isotherm C_b. D_e is calculated from the porosity of cement paste.

The first elementary model allows calculating D_e using a macroscopic approach based on the porosity of cement paste. The relation between the effective diffusion coefficient and the porosity has been developed for type-I OPC materials and established through experimental results from concretes and cement pastes.

Table 2
OPC pastes mixes [11–13] for the elementary model of chloride effective diffusion coefficient.

Paste [11]	w/c	Paste [12]	w/c	Paste [13]	w/c
1	0.25	1	0.2	1	0.4
2	0.30	2	0.3	2	0.5
3	0.35	3	0.4	3	0.6
4	0.38	4	0.5	4	0.7
5	0.40	5	0.6		
6	0.42	6	0.7		
7	0.45				
8	0.50				
9	0.60				
10	0.65				

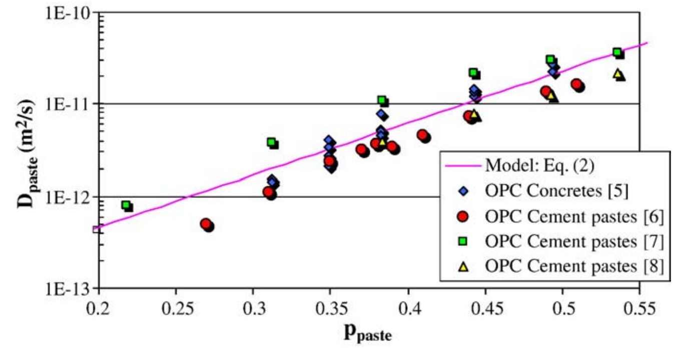

Fig. 1. Chloride effective diffusion coefficient function of the porosity of OPC cement paste (experimental results and model).

The formulations of 20 concretes [10], separated according to the type of OPC cement used, are given in Table 1. The volume fraction of paste v_p is also mentioned. Note the large range of OPC concretes studied, from w/c of 0.35 up to w/c 0.75. Moreover, 20 results from OPC cement pastes have been studied [11–13] with also a large range of w/c from 0.2 up to 0.7, as compiled in Table 2.

The results of the 40 experimental chloride diffusion coefficients are presented on Fig. 1. The following relation, reported on Fig. 1, is proposed for the calculation of the diffusion coefficient in the cement paste (m²/s):

$$D_{paste} = e^{(13 \cdot p_{paste} - 31)} \tag{2}$$

In Eq. (2), p_{paste} is the porosity of the cement paste. In the case of concrete, assuming the porosity is only due to the paste, p_{paste} is deduced from the porosity of concrete accessible to water and the volume fraction of paste v_p. In addition, the concrete diffusion coefficient is calculated using the relation proposed by Bruggeman [14] which considers the combined effect of dilution and tortuousness linked with the addition of aggregates:

$$D_e = D_{paste} \cdot v_p^{3/2} \tag{3}$$

The binding isotherm is calculated by the Hirao relation [15], which gives the amount of chloride bound by hydrates (y in mmol/g) in cement paste:

$$y = 0.616 \cdot \frac{2.65 \cdot x}{1 + 2.65 \cdot x} \cdot \frac{a}{100} + 0.589 \cdot x^{0.58} \cdot \frac{1000}{623} \cdot \frac{b}{100} \tag{4}$$

where x is the chloride concentration in solution (mol/l), a the amount of C–S–H (mass% of cement), and b the amount of AFm (mass % of cement). Chloride binding by AFm is attributed to the formation of Friedel's salt whereas chloride binding by C–S–H is reported to be physical sorption. Assuming that a cement paste is mainly composed of C–S–H, $Ca(OH)_2$, AFm, and AFt (or hexahydrates C_3AH_6), it is possible to estimate a and b by solving the system of Eq. (5) which gives these four hydrated phases of OPC from the cement composition [16]:

$$\begin{cases} CaO = CH + 1.65C - S - H + 4AFm + 6AFt(\text{or } 3\ C_3AH_6) \\ SiO_2 = C - S - H \\ 2Al_2O_3 = 2AFt\ (\text{or } 2C_3AH_6) + 2AFm \\ SO_3 = 3AFt(\text{or } 0C_3AH_6) + AF > m \end{cases} \tag{5}$$

The system is solved presuming the presence of AFt. If the quantity of sulphate is insufficient and the system cannot be solved, we consider the predominant presence of C_3AH_6. Moreover, we worked with mature concrete, so the quantities found for the four hydrates were balanced using the degree of hydration of the cement α,

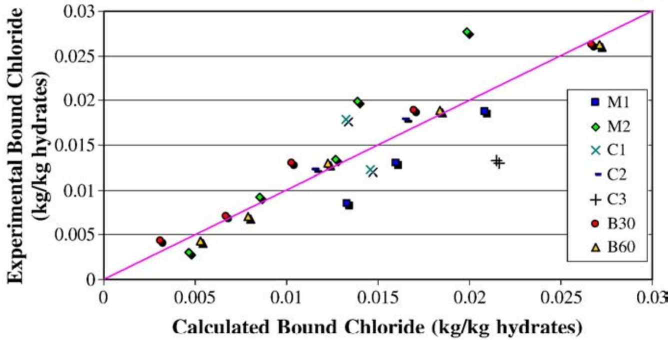

Fig. 2. Experimental bound chloride vs. calculated bound chloride.

calculated from the expression proposed by Waller for OPC at 28 days, depending on the w/c ratio [17]:

$$\alpha = 1 - e^{\left(-3.15 \cdot \frac{w}{c}\right)} \quad (6)$$

It is worth noting that all these phenomenological laws, despite their simplicity of application compatible with the probabilistic methodology, were chosen for their physical meaning. It allows a sufficiently large number of material characteristics to be taken into consideration and to reduce the model discrepancy (see Fig. 1). This discrepancy can be attributed to the materials parameters variability. The accuracy of the elementary models is exposed into the following section with the corresponding definition of the random variables.

3. The probabilistic approach

3.1. Validation of elementary models and random variables

A literature search allowed us to validate the elementary models and estimate the distribution laws of the previous model's parameters. First of all, considering the effective diffusion coefficient calculated by the elementary model and the experimental results found in the literature, we can define the multiplicative error Err_D:

$$D_{e_{\text{experimental}}} = Err_D \cdot D_{e_{\text{calculated}}} \quad (7)$$

$D_{e_{\text{experimental}}}$ corresponds to the 40 experimental points in Fig. 1 and $D_{e_{\text{calculated}}}$ to the trend line. Fig. 3(a) shows the histogram of values taken by Err_D. The Err_D random distribution can be fitted by a lognormal distribution law with a mean of 1.02 and a standard deviation of 0.42.

Similarly, Eqs. (4)–(6) allowed us to compute the amount of bound chloride for a given OPC material. Thus, we can define a multiplicative error on the binding equations:

$$C_{B_{\text{experimental}}} = Err_C \cdot C_{B_{\text{calculated}}} \quad (8)$$

The amount of calculated bound chloride is compared with the experimental one in Fig. 2. 24 experimental points were taken from [18–21] where chloride isotherms were measured using the most widespread technique [22] on mortars (M1, M2) and concretes (C1, C2, C7, B30, B60) (see Table 3 for details of formulations). The chemical characteristics of the 5 type-I OPC studied are reported in Table 4.

Fig. 3(b) shows the histogram of Err_C which can be fitted by a lognormal law with a mean of 1.01 and standard deviation of 0.22. The mean value of 1.01 means that Eqs. (4)–(6) are able to suitably predict the amount of bound chloride.

These distribution laws of Err_D and Err_C were validated at a 5% risk by two tests, the χ^2 test and the Shapiro–Wilk test [23,24].

Finally, the distribution law of porosity was directly obtained using the results of the concrete water porosity measurements, calculated from three masses according to AFREM recommendations [25]: apparent mass of saturated concrete samples after immersion (liquid saturation under vacuum) (M_{water}), mass in the air while they were

Table 3
Formulations of mortars and concretes [18–21] for comparison with the elementary model of chloride binding isotherm.

Composition	Cement type	Cement (kg/m^3)	Aggregates (kg/m^3)	w/c
M1	52.5 PM ES	450	1695	0.35
M2	42.5	450	1695	0.36
C1	“HS65”	450	1854	0.35
C2	“HS65”	420	1851	0.40
C7	“EZ375”	265	1900	0.75
B30	52.5 N	470	1819	0.35
B60	52.5 N	440	1813	0.40

Table 4
Cements characteristics [18–21] for comparison with the elementary model of chloride binding isotherm.

Components (%)	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	L.o.i.
52.5 N [18]	63.71	20.30	5.26	2.24	1.12	3.49	1.1	0.08	2.20
52.5 PM ES [19]	64.60	21.20	3.50	4.60	0.60	2.65	0.63	0.17	1.10
42,5 [20]	64.10	19.60	4.80	3.20	0.90	3.30	0.60	0.20	2.60
“HS65” [21]	63.27	21.41	5.57	3.34	1.40	2.80	0.79	0.33	0.98
“EZ375”	61.55	19.41	4.93	2.86	1.85	3.00	1.79	0.32	0.69

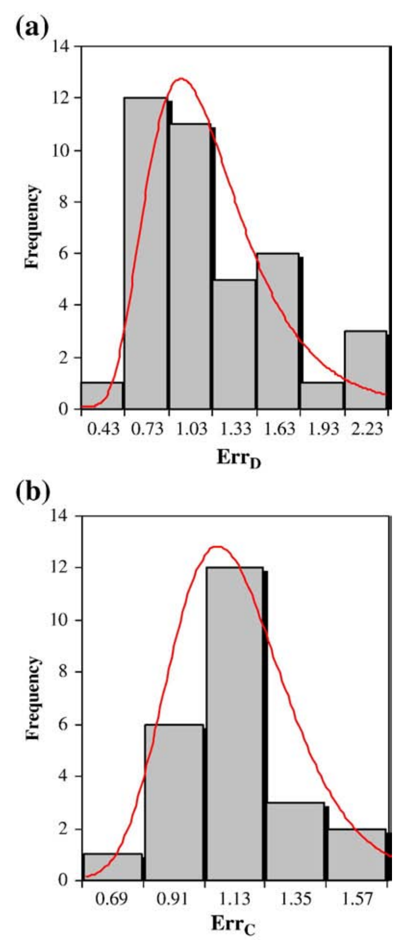

Fig. 3. Histograms of elementary model errors. (a): histogram of Err_D. (b): histogram of Err_C.

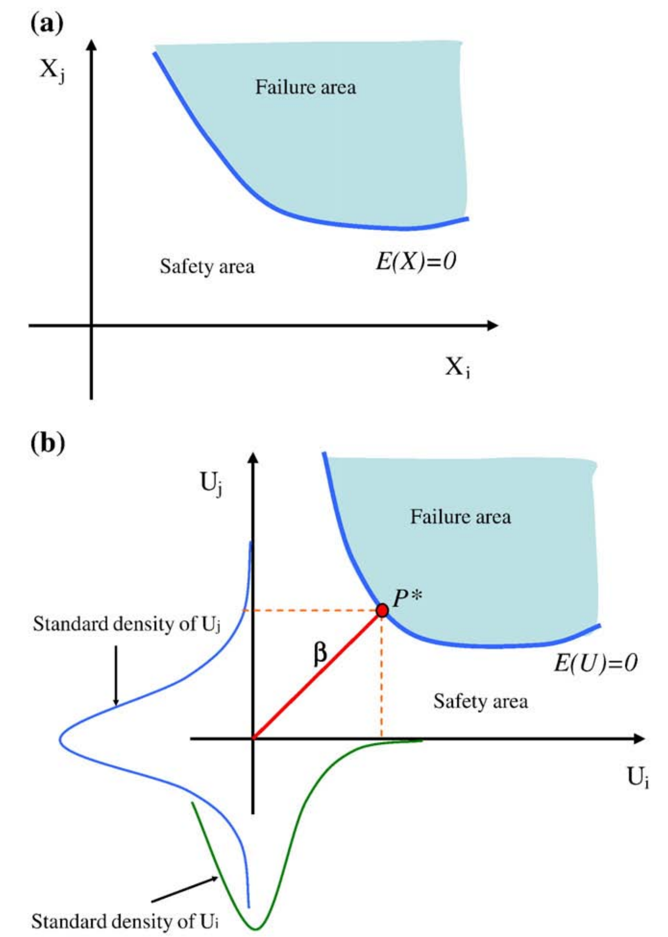

Fig. 4. Reliability index definition. (a): two dimensional space of random variables. (b): standard space for two variables.

still soaked (M_{air}), and mass of dry samples (M_{dry}). The water porosity p is given by the following equation:

$$p = \frac{M_{air} - M_{dry}}{V} = \frac{M_{air} - M_{dry}}{M_{air} - M_{water}} \quad (9)$$

In most general cases, the distribution of the experimental values of porosity is a lognormal law (for example, see experimental results in [18,25]).

Moreover, we are going to see in the next section that the thickness of the concrete cover c_{nom} (as designated in [3]) must be taken into account because we need to define the depth of the reinforcement bars for the corrosion problem. c_{nom} is also considered as a random variable, the mean value being defined according to the actual design rules [3]. The distribution law is lognormal and the coefficient of variation is generally taken to be 20% [26].

Table 5
Concrete mix proportions.

Composition (kg/m^3)		
Cement	CEM I 52.5 PM ES	425
Sand	0/4 mm	760
Gravel	4/20 mm	1152
Superplasticizer		6
Water		145

Table 6
Cement characteristics.

Components (%)	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	Loss on ignition
CEM I 52.5 PM ES	64.60	21.20	3.50	4.60	0.60	2.65	0.63	0.17	1.10

3.2. Calculation of probability of failure

The probabilistic method is necessary to take into account the distribution laws of the input parameters of the chloride ingress model in order to assess the probability of corrosion initiation for a given period of exposure. This is the probability that the quantity of chlorides on the first concrete reinforcement bars reaches a critical chloride concentration value. The probability calculation needs to define a performance function $E(X)$. The state of the concrete, which depends on the realisation of the random variables (represented by the vector X), can belong to two domains: a “failure” set ($E(X) \leq 0$) or a “safe” set ($E(X) > 0$). The frontier where $E(X) = 0$ is called the failure surface (Fig. 4(a) gives a symbolic representation for two random variables). The probability of failure P_f is expressed by:

$$P_f = (E(X) \leq 0) \quad (11)$$

In addition, P_f can be estimated through a reliability index β; the Hasofer–Lind index is generally used. This is defined in the standard space (all variables are transformed into normalized and uncorrelated variables, represented by the vector U, using Nataf's transformation [27]) as the minimum distance from the origin to the failure surface (see Fig. 4(b)). So P^*, called the design point, is the point where the failure is the most probable. Moreover, if β is high, corresponding values of β are far from the median values, so the probability of failure is low.

P^* and β are obtained by a linear optimization method described in detail in [28].

The probability of failure (P_f) is linked to the reliability index β through the standard normal distribution function. We can write the following relation:

$$P_f = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{-\beta} e^{-\frac{t^2}{2}} \mathrm{d}t \quad (12)$$

In the case of chloride diffusion, according to the definition of the performance function E used previously to calculate P_f, we need to choose a critical chloride concentration. We chose the value of 0.4% of the weight of cement for total chlorides. Data published by several authors show that the critical concentration may lie within a broad range, namely 0.35 to 3% by weight of cement [29,30]. The influence of several factors, such as concrete mix proportions, C_3A content of the cement, w/c ratio, relative humidity, temperature or the definition or the threshold itself, are the different reasons for this variability. Because of the wide scatter of the values and the lack of consistent statistical data, the use of the lower boundary the most observed for corrosion initiation (0.4% by weight of cement for total chlorides) seems relevant for practical application.

Table 7
Random variable distributions.

Variable	Distribution	Mean	Standard deviation
Porosity p	Lognormal	9.5%	0.38%
Err_D	Lognormal	1.02	0.42
Err_C	Lognormal	1.01	0.22
Cover c_{nom}	Lognormal	5 cm	1 cm

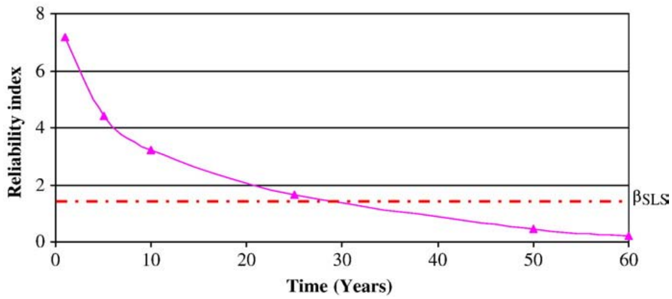

Fig. 5. Time variation of the reliability index.

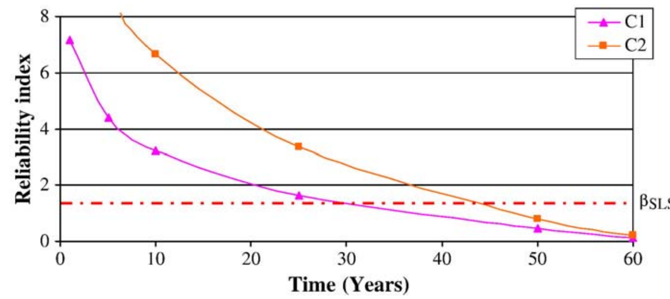

Fig. 6. Effect of the quality of execution on reliability. C1: idem Fig. 5; C2: 10% for coefficients of variation.

Finally, the four random variables defined in Section 2 remain: the porosity p, the error on the effective diffusion coefficient Err_D, the error on the amount of bound chlorides Err_C, and the concrete cover thickness c_{nom}. Hence, the performance function in our study can be expressed, for a given exposure period, by:

$$E(p, Err_D, Err_C, c_{nom}) = 0.4 - C_{total,cover}(p, Err_D, Err_C, c_{nom}) \quad (13)$$

where the concentration of total chloride at the cover depth $C_{total,\,cover}$ is expressed in % of weight of cement.

4. Practical application

4.1. Description of data

In this section, we are going to illustrate the methodology through the example of concrete exposed to a marine environment. The concrete used for this study was a high-performance concrete with a w/c ratio of 0.4, the composition of which is given in Table 5. The cement was a type-I OPC (CEM I 52.5 PM ES, according to European standard EN 197-1) and its chemical characteristics are reported in Table 6. This concrete was assumed to be submerged in sea water.

The chloride concentration on the exposed surface was 480 mol/m^3, chosen to correspond to the oceans' average salinity of 35 g/l, with 27 g/l of NaCl. Note that this value is deterministic although the salinity may fluctuate locally (near an estuary for example) but remains almost constant for a given geographical position. In the previous section, the four random variables governing the chloride diffusion were exposed: p, Err_D, Err_C and c_{nom}. The concrete cover thickness chosen c_{nom} was 5 cm, according to the value recommended in the design rules for marine environments [3]. The measured porosity was 9.5% with a standard deviation of 0.38%. Information concerning distributions, means and standard deviations are summed up in Table 7.

4.2. Reliability results

The variation of the reliability index (β) with exposure time is presented in Fig. 5. This index is relevant to the risk of occurrence of corrosion initiation in the reinforcing steel as explained in Section 4. A significant decrease in the reliability can be seen with time: the value of the reliability index after 1 year is close to 7 and drops to 0.5 after 50 years, which corresponds to a probability that 30% of concretes will be subject to possible corrosion initiation after 50 years of exposure (Eq. (12)). Note, for example, the threshold value 1.5 ($P_f \approx 7\%$, β_{SLS} in Fig. 5) recommended by the Eurocodes for Serviceability Limit States (SLS) at 50 years [31]. The reliability index found is lower than this boundary after 28 years of exposure. This means that the recommended cover does not seem to be sufficient to ensure the reliability level recommended by the Eurocodes.

Probabilistic sensitivity factors are also available in the probabilistic method. It allows classifying the importance of the model parameters to reach the limit state. In Table 8, we can see that the most influential parameter is the effective diffusion coefficient (trough Err_D) and the concrete cover. This emphasises the facts that respecting the concrete cover depth is essential and that the simplest way to improve reliability is increase the cover depth.

To palliate the lack of reliability with respect to the SLS for the present structural design, a logical direction may be to improve the quality of execution, which should lead to a reduction of the standard deviation of parameters like the concrete physical properties or the cover depth. For industrial processes and precast concretes, the effect of a decrease to 10% of the coefficient of variation for each random variable is shown in Fig. 6. We can observe the beneficial effect of a good quality of execution, which remains significant for 40 years. After this date, standard deviations are no longer influential because the limit state can be reached even with model parameters close to the median values of the random distributions. In other words, even with quasi-deterministic parameters, the limit state will be reached if the exposure duration is sufficient but, the larger the standard deviations, the sooner the limit state can be reached.

To comply with the Eurocodes reliability level, we can increase the cover depth. Fig. 7 shows the evolution of the reliability index at 50 years versus the cover depth. It appears that a design corresponding to $\beta = 1.5$ requires 6.5 cm.

Table 8
Sensitivity factors.

Variable	Sensitivity factor
Porosity p	0.06
Err_D	0.46
Err_C	0.01
Cover c_{nom}	0.47

5. Conclusion

In this work, we have presented a complete methodology for the durability design of cover depth for a concrete immersed in sea water.

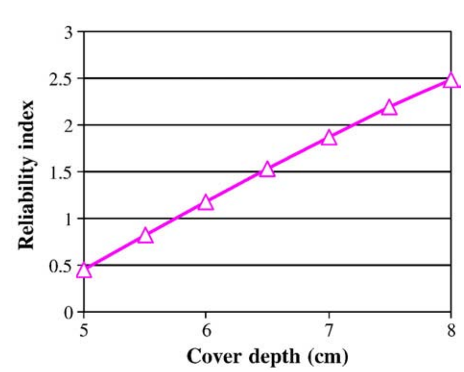

Fig. 7. Evolution of reliability with cover depth at 50 years.

Knowledge of the distribution laws of the different model parameters is fundamental to the success of this method. The concrete service life is quantified objectively through the reliability index β. To play its role correctly, β takes into account all the uncertainties due to the quality of execution and the experimental measurements. Using elementary models and a statistical interpretation of the literature data allowed us to apply the approach while limiting the number of experiments to the acquisition of the water porosity statistical distribution. At present, the application is available for OPC-based concretes but the methodology will be extended in our following works, firstly to other cements in marine structures (OPC+fly ash, OPC+BBFS) and secondly to unsaturated concrete for splash zones. To finish, we would like to stress the fact that this type of probabilistic approach is the only one that is able to objectively provide both a robust numerical model and the variability of its parameters, supplying civil engineers with a new tool for designing structures under durability constraints.

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