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Abstract

The aim of this study is to develop a new design procedure for the durability of the Reinforced Concrete (RC) structures in aggressive environments. The study approach developed here includes: (i) a qualitative analysis phase to characterize the design parameters and environmental exposure conditions of

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RC structures; (ii) a quantitative analysis phase, to establish the relationship between service life and design parameters and environmental exposure conditions using the service life prediction model firstly, and then to determine the most influential design parameters on service life using sensitivity analyses; and (iii) a final design phase, to design RC structures using some favorable values of the most influential design parameters firstly, and then to compare the service life thus obtained with that of RC structures designed using a standardized approach. An application is also proposed on simulated RC structure exposed to carbonation in Madrid (Spain). This RC structure follows the recommendations of the European standard EN 206-1 for XC4 exposure class. The sensitivity analysis results are discussed in detail including influence trends, importance ranking, non-monotonic effects and parameter interaction influences. The most influential design parameters obtained are cement strength class (f_{cem}), water-to-cement ratio (W/C) and cement type (CEM). By using W/C of about 0.4, f_{cem} of about 52.5 MPa and CEM I cement type instead of their limiting value as recommended by EN 206-1, the service life of the RC structure is significantly improved.

Key words: Carbonation; Durability design; Corrosion; Service life. Morris analysis, Sobol indices.

1. Introduction

In the literature, two basic approaches are proposed for the design of the durability of Reinforced Concrete (RC) structures in aggressive environments [1]: a prescriptive approach and a performance-based approach.

The prescriptive approach is primarily based on the acquired experience in the durability performance of existing RC structures. Because experience is generally insufficient to allow for the quantitative requirements, most of the requirements for durability are formulated in a qualitative and empirical way. In the case of reinforcing steel corrosion due to carbonation or chlorides, the prescriptive approach defines an exposure class and subsequent prescriptions including (i) concrete composition (a maximum water-to-cement ratio, a minimum cement content and a cement type); (ii) a minimum 28-day compressive strength of the concrete; and (iii) a minimum concrete cover depth for service life design [2] [3].

The key feature of the performance-based approach is to assess relevant concrete material properties using some relevant test methods or service life prediction models. This approach can be used to formulate requirements as regards material properties and structure dimensions. In the case of corrosion of reinforcing steel due to carbonation [4] [1] [5] or chlorides [6] [7] [8], the estimation of the deterioration evolution depending on expected influential parameters is mostly performed by applying a probabilistic approach. This estimation makes it possible to formulate requirements for the structural responses depending on the service life design [3]. Then, durability design can be completed in two ways: (i) using a fully probabilistic method, for which the concrete cover depth and the diffusion coefficient of CO_2 or chlorides are usually considered as main probabilistic design parameters for the required service life design and the reliability level [4] [1] [5] [6] [7] [8]; and (ii) using the partial factor method to determine the characteristic values and the partial factors for the design parameters [4] [1] [7].

The strength of the prescriptive approach lies in its flexibility to account for experience and its easy application. The obvious weakness of this approach is that: (i) a simple set of general prescriptions cannot be optimal for all the different parts of a structure exposed to different levels of aggressiveness depending on the structure areas [9]; (ii) our understanding of service durability performance of the structure at the design stage must be improved [1]; and (iii) it does not encourage the use of novel materials for durability design. The strength of the performance-based approach, on the other hand, is its relevance for the durability responses so that service life design can be carried out in a more scientific and reliable way. However, two main difficulties must be faced: (i) a better understanding of the deterioration mechanisms must combine the results of both the scientific research with long-term in-situ observations; and (ii) the uncertainty associated with deterioration mechanisms must be properly taken into consideration in the design process. This last issue can be solved by carrying out a sensitivity analysis of service life in relation to modeling parameters. The Sensitivity Analysis (SA) is the study of how the uncertainty of a mathematical model or system (numerical or other systems) results can be apportioned to different sources of uncertainty and variability of the input parameters [10]. In the literature, many studies present the SA of the simplified diffusion-based corrosion initiation model of RC structures exposed to chlorides. This analysis is conducted to identify, among the different parameters like concrete cover depth, chloride diffusion coefficient, chloride threshold level, and chloride concentration at the surface, those which are the most significant [11] [12]. Other studies describe the SA of corrosion rate prediction models [13] or simplified carbonation models [14] conducted to classify the different influences of the input parameters. Some authors use the "One At a Time (OAT)" SA method [11] [12], which provides some semi-qualitative sensitivity information by varying one parameter at a time while keeping the others constant. Sensitivity is observed graphically. Other authors use the SA method based on the regression analysis [13] [14]. This method quantifies the effect of the input parameters on the model results.

It is sometimes difficult to distinguish between prescriptive or performance-based design approaches. For instance, if the existing RC structures on a given project site have achieved the objective set by service life design, then the durability design of new RC structures can rely on the rational analysis of the durability measurements carried out on these RC structures. Consequently, determining whether structure design is specifically based on the prescriptive or the performance-based approach is difficult, in this case. The experimental data on the durability performance of the structures thus collected must be integrated into the different phases of the performance-based approach to determine the preliminary dimensions of the structure [3]. Thus, both approaches are useful as regards durability design and are complementary methods in the global design process.

The present paper reports a study conducted to develop a new design procedure for the durability of the RC structures in aggressive environments. The procedure discussed here is the result of the combination of both prescriptive and performance-based approaches. Qualitative and quantitative SA methods are integrated into the design procedure to determine durability action levers (refer to definition of “action levers” in *Appendix*). These are used to design the best durable RC structure.

The new design procedure for the durability of RC structures in aggressive environments is presented in Section 2. An application of this procedure to a simulated RC structure exposed to carbonation in Madrid (Spain) is described in Section 3. Some recommendations for the durability design according to EN 2016-1 for XC4 exposure class are discussed in Section 4.

2. Development of the new durability design procedure

The durability design procedure proposed here includes: (1) a qualitative analysis, (2) a quantitative analysis, and (3) a final design procedure (*Figure 1*). The purpose of the qualitative analysis is to determine the preliminary dimensions of a RC structure at a general level within the context of aggressive environments. It also includes the characterizations of the design parameters and the environmental exposure conditions. This analysis is carried out using a prescriptive approach. The quantitative analysis aims at establishing a relationship between the aggressive environment and the service life of structure using a service life prediction model [4]. The purpose of the quantitative analysis is to determine the action levers by applying the SA method to the service life prediction model. The final design phase consists in using the action levers to redesign the RC structure properties in order to achieve the longest service life possible. This phase also includes a comparison between the service life of a structure designed using the procedure proposed here and that of a structure designed using the recommended limiting values of EN 206-1 [15].

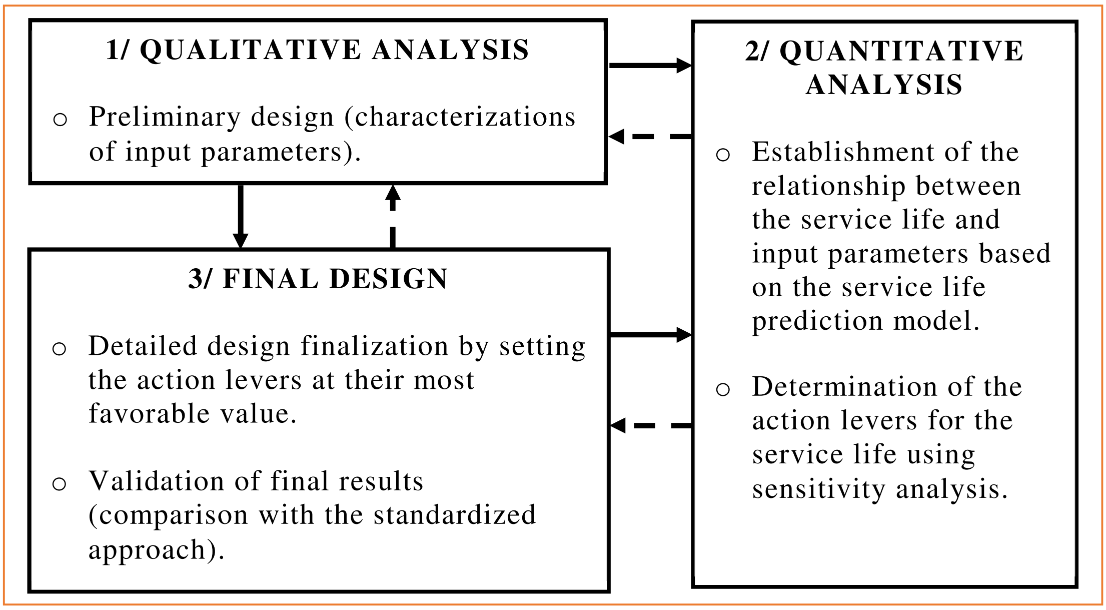

Figure 1. Design procedure for durability of RC structures in aggressive environments.

In order to determine the action levers, suitable SA methods must be selected. They must provide the trend of action levers in relation to the service life, the quantization of their influence and the interactions with other parameters. Thus, the SA methods used in the previous studies [11] [12] [13] [14] are not relevant in this context. Consequently, a combination of two SA methods, Sobol's quantitative method [16] and Morris' qualitative method [17] is chosen. This combination has been previously used for the same purpose in environmental design using Life Cycle Assessment (LCA) [18] [19]. It can provide complementary information on the influence of the input parameters on the model results in the decision-making process. Sobol's method is used to quantify the input parameters contribution to model result variations. Morris' method, on the other hand, provides additional information on the trend of the input parameters. Both methods require that all the input parameters are independent of one another. Both methods are summarized in the next subsections.

2.1. Sobol's quantitative sensitivity analysis

Sobol's method [16] is based on the analysis of the variance decomposition of the model f in order to quantify the contribution of variability of the input parameter X_j to the total variance of the output Y. The individual contribution of input parameter X_j is measured using the first order sensitivity index (S_j) such as:

$$S_j = \frac{Var\left(\mathbb{E}\left[Y \mid X_j\right]\right)}{Var(Y)} \quad (1)$$

where: $Var\left(\mathbb{E}\left[Y \mid X_j\right]\right)$ *is the conditional variance of* Y *produced by the variation of* X_j, $Var(Y)$ *is the total variance of* Y.

The individual Sobol indices lie in the interval [0-1]. Moreover, the overall output sensitivity to the parameter X_j (i.e., including first and higher order effects (interaction) of X_j) can be measured using the total sensitivity index (S_{T_j}) [20] as:

$$S_{Tj} = 1 - \frac{Var\left(\mathbb{E}\left[Y \mid X_{\neq j}\right]\right)}{Var(Y)} \tag{2}$$

where: $Var\left(\mathbb{E}\left[Y \mid X_{\neq j}\right]\right)$ *is the conditional variance of Y produced by the variation of all the input parameters except* X_j*.*

Sobol's method requires to have characterized the Probability Density Function (PDF) of each input parameter. The Monte Carlo simulations are carried out by varying simultaneously all the input parameters according to their PDF and by calculating the associated model results. In this study, S_j and S_{T_j} are calculated.

2.2. Morris's qualitative sensitivity analysis

Morris' method [17] is one of the most popular screening method, which consists in developing a randomized experimental design process by varying one parameter while keeping the others constant (OAT method) over a certain number of repetitions k ($k = 1,2, \ldots, r$). Then, the variation coefficients, called the elementary effects ($\mathbb{EE}_j^{(k)}$), are obtained as:

$$\mathbb{E}\mathbb{E}_j^{(k)} \approx \frac{f\left(\mathbb{X}^{(k)} + e_j.\Delta\right) - f\left(\mathbb{X}^{(k)}\right)}{\Delta} \tag{3}$$

where: Δ is a pre-defined step, e_j is a vector of zero but with j-th equal ±1.

The mean value (μ_j) of the elementary effects is calculated to determine the trend of input parameter X_j. The algebraic sign of μ_j indicates increasing (positive sign) or decreasing (negative sign) trends of the model output related to X_j. The standard deviation value (σ_j) of the elementary effects is the measure of the sum of all the interactions of X_j with the other parameters and of all non-linear influences. We find:

$$\mu_j = \frac{1}{r}\sum_{k=1}^{r} \mathbb{E}\mathbb{E}_j^{(k)} \tag{4}$$

$$\sigma_j = \sqrt{\frac{1}{r-1}\sum_{k=1}^{r}\left(\mathbb{E}\mathbb{E}_j^{(k)} - \mu_j\right)^2} \tag{5}$$

In the case of non-monotonic functions, the elementary effects can have an opposite sign for the considered repetition, which can result in a μ_j close to zero if the parameter is influential. In order to prevent this, Campolongo et al. [21] recommend to use the mean value of the absolute value (μ_j^*) of the elementary effects rather than the usual μ_j.

$$\mu_j^* = \frac{1}{r}\sum_{k=1}^{r}\left|\mathbb{E}\mathbb{E}_j^{(k)}\right| \tag{6}$$

The information about the algebraic sign of μ_j is lost when using μ_j^*. However, it is a good indicator for the assessment of the importance of the input parameters in relation to each other. Morris' method requires a local interval range (minimum and maximum value) for each input parameter. The number of repetitions r ranges from 4 to 10 [22]. In this study, μ_j, μ_j^* and σ_j are calculated.

Throughout the rest of the work, Morris and Sobol methods serve to identify input parameters that are major contributors to the variability of service life. More specifically, the controllable parameters related to technological aspects (e.g., concrete mix, size of structure), i.e., the "technological parameters", are considered as action levers if they are major contributors to the service life.

2.3. Identification of action levers using sensitivity indices

Based on the Sobol indices, the technological parameters are identified as action levers, if the value of S_j is higher than 10%. Moreover, if the value of S_j is lower than 10% but the difference ($S_{T_j} - S_j$) is high, i.e., assumed to be greater than 10%, they can also be considered as potential action levers [18] [19]. This means that parameter X_j is not individually influential but has a non-negligible global contribution because of its interaction with the other parameters. As regards the Morris indices, the parameters with a higher μ_j^* are considered as potential action levers [17]. If the parameters satisfy the condition $\sigma_j \geq |\mu_j|$, they are considered to have a non-monotonic effect. In contrast, non-influential input parameter X_j is assumed to have indices S_{T_j} lower than 10% and μ_j^* low in relation to other indices $\mu_{i,i\neq j}^*$ of input parameters $X_{i,i\neq j}$. Recall that Morris indices μ_j^* and μ_j have the same order of magnitude than the model response while the first order Sobol indices S_j are normalized and lie in the interval [0-1].

3. Case study

3.1. Presentation of the case study

The case study studied here consists of a RC structure subjected to carbonation. The structure is assumed to be located in Madrid (Spain) because this location presents optimal environmental conditions for carbonation of concrete [23] [24]. Madrid, indeed, is a place with a high level of carbon dioxide [25] and with an average relative external humidity of about 0.56 [26]. The considered structure follows the recommendations of EN 206-1 for XC4 exposure class [15]: concrete is exposed to the air and the structure is not sheltered from rain. Carbonation is the only alteration phenomenon of RC structure considered in this paper. The objective here is to identify the action levers affecting service life to obtain the longest service life possible by setting the identified action levers at their most favorable value.

The service life of a structural component is the period after construction, during which all the structure properties, when routinely maintained, are higher than the minimum acceptable values [2]. Tuutti [27] proposed a simplified model for predicting the service life of RC structures, considering the degradation due to carbonation induced corrosion. Service life is divided into two periods: initiation period and propagation period as shown in *Figure 2*. There are two periods because the mechanisms involved are different in physical-chemical terms. The initiation period corresponds to the penetration of CO_2 into the concrete cover until the carbonation front reaches the reinforced layer. The propagation period includes (i) steel corrosion; (ii) cross section loss; (iii) concrete surface cracking; and (iv) spalling of concrete cover.

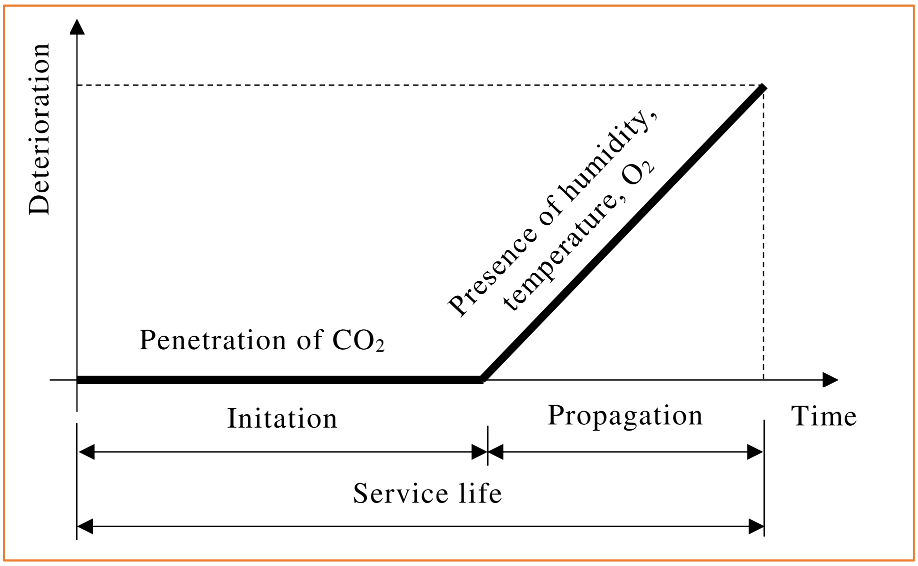

Figure 2. Tuuti's service life prediction model [27].

Our case study deals with the initiation period only. The service life of RC structure is limited to the corrosion initiation period. Thus, a model for the initiation period is required: that model calculates at any time the carbonation depth within concrete.

3.2. Qualitative analysis: characterization of input parameters

The service life considered here is predicted using the carbonation model recently developed by Ta et al. [28] (*Figure 3*). This carbonation model is validated using data from the literature on short and long-term natural carbonation exposure conditions. Most of the experimental data concern CEM I, CEM II, CEM III cement types. The prediction of this carbonation model for estimation of carbonation depth is more accurate than Papadakis' model [29] and Yang's model [30]. This model takes many influencing design parameters of the carbonation process into account and predicts the natural carbonation depth. It is based on the analytical solution of Fick's law given by:

$$x = \sqrt{\frac{2 \times D_{CO_2} \times CO_2}{a}} \times \sqrt{t} \qquad (7)$$

where: x (m) is the carbonation depth within concrete, D_{CO_2} (m^2/s) is the CO_2 diffusion coefficient of concrete, CO_2 (kg/m^3) is the CO_2 concentration in the atmosphere, a (kg/m^3) is the amount of CO_2 absorbed in a unit volume of concrete, t (s) is the exposure time.

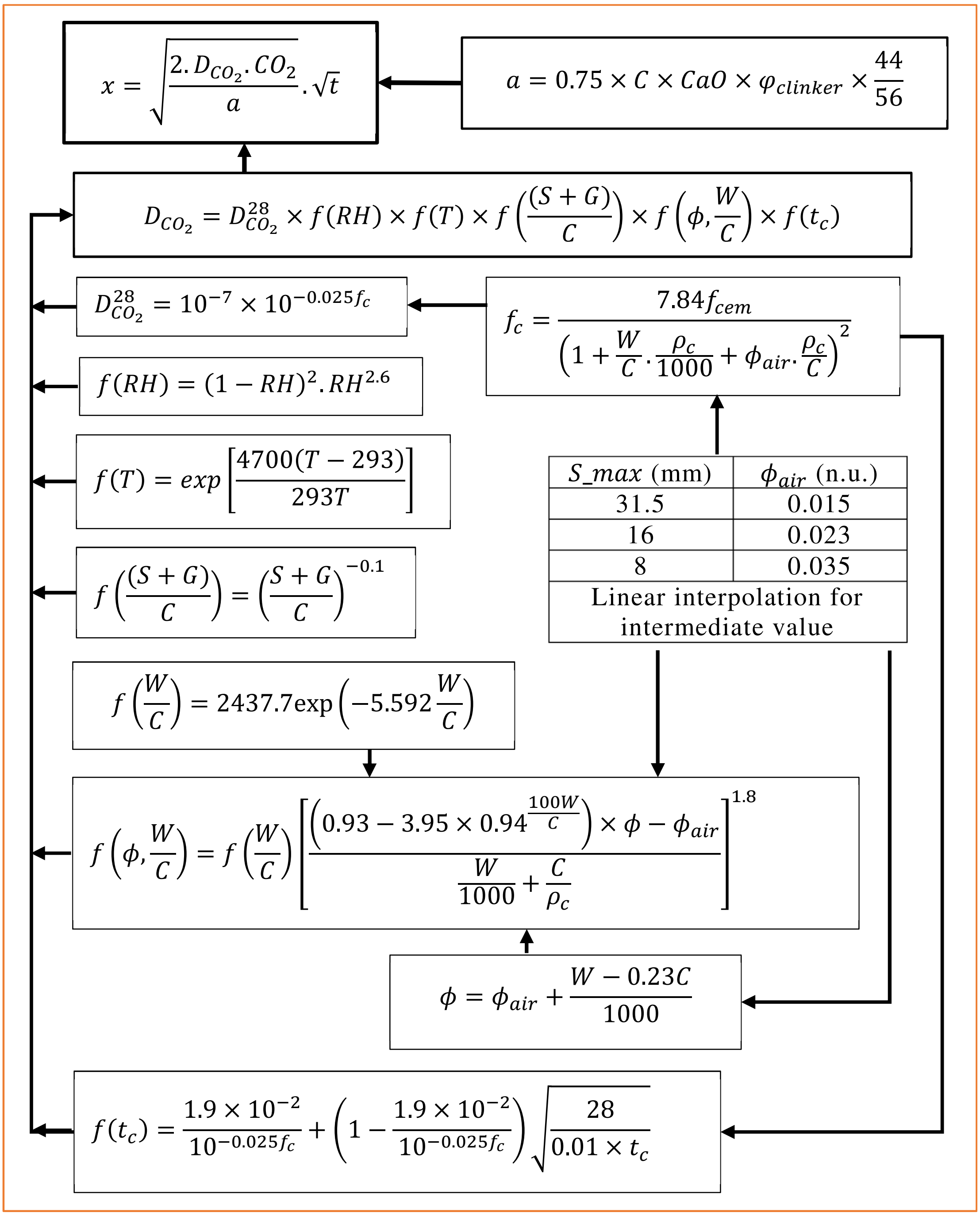

Figure 3. Carbonation model presented in [28] (input parameters are detailed in the text).

When the carbonation depth is equal to the concrete cover depth (d), i.e., $x = d$, the corrosion initiation period ends. The steel reinforcement could be then corroded with the presence of O_2, humidity and temperature as defined by Tuuti's service life prediction model (*Figure 2*). Service life (t_{ser}) can be written as:

$$t_{ser} = \frac{d^2 \times a}{2 \times D_{CO_2} \times CO_2} \tag{8}$$

The purpose then is to design a concrete structure with a maximum service life value t_{ser}.

Many parameters are required for the calculation of D_{CO_2} and a as shown in *Figure 3*. For the application of Sobol and Morris' methods to the determination of the sensitivity of t_{ser} to input parameters, we use only the expression of D_{CO_2} and a in relation to the independent parameters. An independent parameter does have a relationship with other independent parameters. The dependent parameters are expressed through the independent parameters. The time dependency of the input parameters is not taken into account. Consequently, the expression of t_{ser} takes the form:

$$t_{ser} = f(C, W/C, S/G, S\_max, CEM, f_{cem}, d, t_c, T, RH, CO_2) \tag{9}$$

or

$$t_{ser} = f(X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, X_{11}) \tag{10}$$

where: C (kg/m^3 of concrete) is the amount of cement content, W/C (n.u.) (n.u. = no unit) is the water-to-cement ratio, S/G (n.u.) is the sand-to-gravel ratio, S_max (mm) is the maximum aggregate size, CEM (n.u.) is the cement *type,* f_{cem} *(MPa) is the cement strength class,* t_c *(days) is the initial curing period, T (K) is the ambient temperature, RH (n.u.) is the relative external humidity.*

The input parameters, including the technological and environmental parameters (refer to definition of “technological and environmental parameters” in *Appendix*), characterized by determining the variability range and the PDF of each parameter as summarized in *Table 1*. The technological parameters are characterized by the limiting values recommended by EN 206-1 [15] for XC4 exposure class and the statistical analysis of the studies addressing the problem of concrete carbonation found in the literature. To provide the action levers, a uniform (discrete or continue) distribution is usually set for the technological parameters because they are chosen by the designer. Thus, all the values within the distribution interval are considered equally probable. The interval is determined by minimum and maximum values.

The environmental parameters are characterized from weather data [26], which include the ambient temperature (T) and the relative external humidity (RH). The CO_2 concentration in the atmosphere (CO_2) is taken from [25].

Table 1. Input parameter characterization.

Parameter	**Unit**	**Probability Density Function (PDF)**	**Reference**
Technological parameters			
Group 1: concrete mix			

X_1	C	kg/m^3	$\mathcal{U}$ (min = 300; mean = 404.5; max = 509)	[15]
X_2	W/C	n.u.	$\mathcal{U}$ (min = 0.4; mean = 0.45; max = 0.5)	[15]
X_3	S/G	n.u.	$\mathcal{U}$ (min = 0.5; mean = 1.3; max = 2.1)	
X_4	S_max	mm	$\mathcal{U}$ (min = 20 ; mean = 26; max = 32)	[15]
Group 2: cement				
X_5	CEM	n.u.	$d\mathcal{U}$ (10 cement types)	[15]
X_6	f_{cem}	MPa	$d\mathcal{U}$ (3 strength classes)	[15]
Group 3: concrete cover depth and initial curing period				
X_7	d	m	$\mathcal{U}$ (min = 0.05; mean = 0.065; max = 0.08)	[31] [32]
X_8	t_c	days	$\mathcal{U}$ (min = 1; mean = 2; max = 3)	[33]
Environmental parameters				
X_9	T	K	$tr\mathcal{N}$ (mean = 287.4; CoV = 0.03; min = 272.4; max = 309.1)	[26]
X_{10}	RH	n.u.	$tr\mathcal{N}$ (mean = 0.56; CoV = 0.33; min = 0.2; max = 0.88)	[26]
X_{11}	CO_2	ppm	$tr\mathcal{N}$ (mean = 380; CoV = 0.05; min = 304.6; max = 456.8)	[25]

Notes:

1. CoV = Coefficient of Variation; $tr\mathcal{N}$ = truncated Normal distribution; $\mathcal{U}$ = Uniform distribution; $d\mathcal{U}$ = discrete Uniform distribution.
2. The variability range of X_1, X_2 and X_3 parameters also comes from the statistical analysis conducted by some experimental investigations found in the literature (detailed in the text).

Group 1: concrete mix

The requirements for concrete of EN 206-1 [15] for XC4 exposure class are a maximum water-to-cement ratio (W/C) of about 0.5, a minimum amount of cement content (C) of about 300 kg/m^3 and maximum aggregate size (S_max) within the range 20-32 mm. Previous studies [4] [34] [35] [36] reveal that (i) CEM I cement type concrete with a water-to-cement ratio (W/C) lower than 0.4 has very high carbonation resistance; and (ii) concrete using CEM I cement type has higher carbonation resistance than the other cement types containing additions. In this work, we thus assume the minimum W/C of about 0.4 for cement types considered in order to observe the carbonation phenomenon; however, the carbonation phenomenon can appear for W/C values lower than 0.4 for other cement types. Moreover, concrete casted with such W/C is uncommon. Based on the statistical analysis of seventeen experimental investigations on concrete carbonation [37] [5] [38] [39] [40] [41] [42] [43] [44] [45] [24] [46] [47] [48] [1] [49] [50], the maximum cement content (C) is about 509 kg/m^3 and the sand-to-gravel ratio (S/G) varies between 0.5 and 2.1.

Group 2: cement

In the carbonation model proposed by Ta et al. [28], the cement type (CEM) is considered through the following three parameters: amount of Portland clinker inside cement, amount of calcium oxide per weight of cement and cement density. Therefore, among the 27 cement products presented in [51], ten cement types are considered: CEM I; CEM II/A; CEM II/B; CEM III/A; CEM III/B; CEM III/C; CEM IV/A; CEM IV/B; CEM V/A; and CEM V/B. The characteristics of these cements are presented in *Appendix* (*Table A1*).

Cement strength class (f_{cem}) of all these cement types is available for strength classes of 32.5 MPa, 42.5 MPa and 52.5 MPa.

Group 3: concrete cover depth and initial curing period

The concrete cover depth (d) must have a minimum thickness to protect the steel reinforcements from the CO_2 attack and to prevent the corrosion of steel reinforcements [52]. This design parameter varies according to the exposure class, the quality of construction and the intended service life [52]. Combined to the requirements for concrete of EN 206-1 [15] for XC4 exposure class, the minimum recommended concrete cover depth (d) ranges from about 0.05 m [31] to 0.08 m [32] for structure design with an expected 100-year service life. Consequently, d can vary between 0.05 and 0.08 m in this study.

Because of a limited construction time, the initial curing period (t_c) varies between 1 day and 3 days [33].

3.3. Quantitative analysis

3.3.1. Service life prediction and sensitivity analysis

Eq. (10) is used to establish the relationship between the service life (t_{ser}) and the input parameters X_j presented in *Table 1*. In Sobol' method, the t_{ser} values are simulated using *Eq. (10)* by varying all input parameters simultaneously according to their PDF (*Table 1*).

The first order Sobol sensitivity index (S_j) (*Eq. (1)*) and the total Sobol sensitivity index (S_{T_j}) (*Eq. (2)*) are calculated as described in *Section 2.3*. They are calculated by means of a bootstrap method with 500 replications from a half-sample (5,000) taken from an initial sample of about 10,000 as recommended in [18].

In Morris' method, the t_{ser} values are simulated using Eq. (10) by varying each input parameter one at a time. Then the mean value (μ_j) (*Eq. (4)*), standard deviation value (σ_j) (*Eq. (5)*) and mean value of the absolute value (μ_j^*) (*Eq. (6)*) of the elementary effects are calculated as described in *Section 2.3*. They are calculated by means of discretization of the input parameters X_j in 10 values with a prescribed number of trajectories of about 30 as recommended in [18].

3.3.2. Determination of the action levers

Our results shown in *Figure 4* are related to the case study. It is important to note that SA results depend on both PDF of input parameters given in *Table 1* and on carbonation model chosen.

Figure 4 displays the SA results.

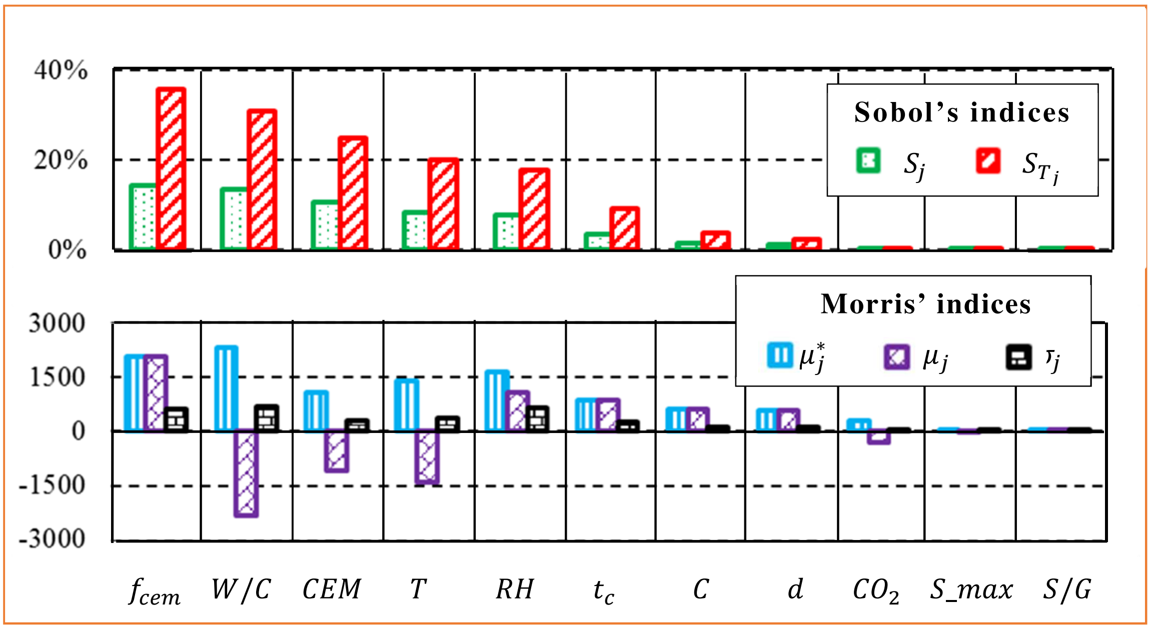

Figure 4. Sobol and Morris sensitivity indices.

Figure 4 shows that cement strength class (f_{cem}), water-to-cement ratio (W/C), cement type (CEM), ambient temperature (T) and relative external humidity (RH) (in descending rank) are the most influential parameters because their S_{T_j} and μ_j^* values are the highest. The difference $S_{T_j} - S_j$ is around 22% for cement strength class (f_{cem}), 17% for water-to-cement ratio (W/C), 14% for cement type (CEM), 12% for ambient temperature (T) and 10% for relative external humidity (RH). This means that their interactions with the other parameters are important. Parameters f_{cem}, W/C and CEM are considered the most influent with a S_j value above 10%. They are thus technological parameters (i.e., controllable parameters) identified as action levers. T and RH are environmental parameters (uncontrollable parameters) that are uncertain. The less-influential parameters ($S_{T_j} < 10\%$ and low μ_j^*) are initial curing period (t_c), cement content (C), concrete cover depth (d), CO_2 concentration in the air (CO_2), maximum aggregate size (S_max) and sand-to-gravel ratio (S/G). Based on the algebraic sign of μ_j, we observe that an increase in RH, C, d, t_c, and S/G and a decrease in W/C, S_max, T, and CO_2 result in the increase of t_{ser}. All parameters have σ_j/μ_j^* within the interval [0.19 – 0.39]. It indicates that the effects between parameter are monotonic. Because f_{cem} and CEM are discrete parameters, their algebraic sign of μ_j is not significant. Finding favorable value requires testing all of the values of f_{cem} and CEM. The simulation results are displayed in *Figure 5*. We plot the service life on log scale versus clinker content. The service life is represented by its mean value and standard deviation.

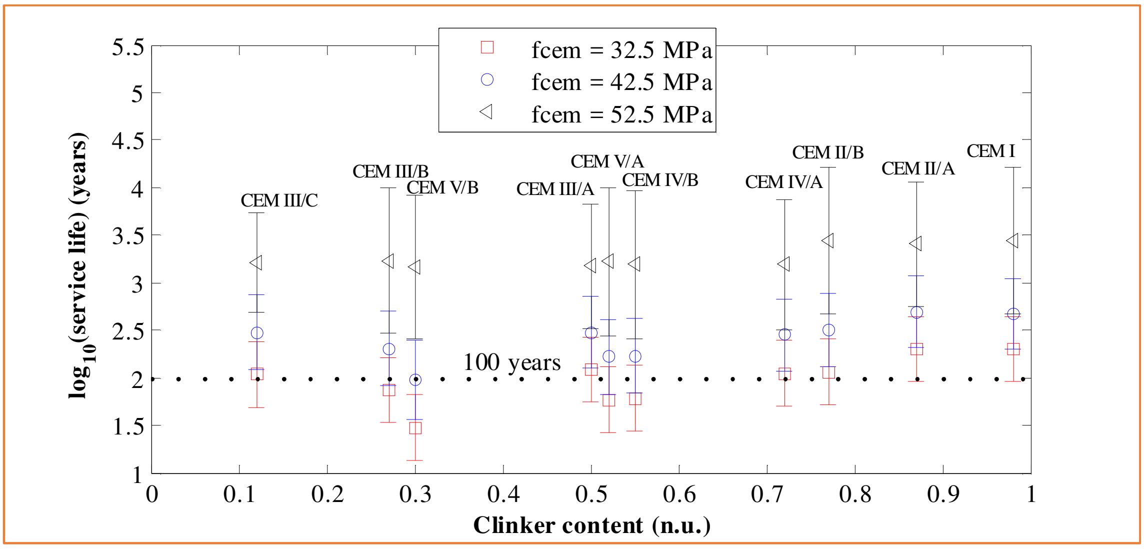

Figure 5. Comparison of service lives of cement strength classes and cement types.

The highest service life is obtained with cement strength class (f_{cem}) 52.5 MPa, followed by 42.5 MPa and 32.5 MPa. The CEM I and CEM II/B cement types are the most favorable to increase the service life with f_{cem} 52.5 MPa. The CEM II/B has lower environmental impacts. These findings are in line with previous study [38]. For both f_{cem} 42.5 and 52.5 MPa we found that service life is higher than 100 years whatever the cement type. However, none of the service lives considering standard deviation obtained with f_{cem} 32.5 MPa is higher than 100 years.

3.3.3. Comparison of the sensitivity analysis results to the literature

This section compares our SA results with the literature. Cement strength class (f_{cem}) and water-to-cement ratio (W/C), two technological parameters, are key parameters for the determination of the concrete porosity and the 28-day compressive strength of concrete (f_c) [9] [53]. Both values, indeed, are important indicators of the evaluation of the resistance to penetration of carbon dioxide into concrete [54]. Higher cement strength class (f_{cem}) and a decrease in water-to-cement ratio (W/C) result in an increase of f_c. For a given water-to-cement ratio (W/C), it has been shown that service life (t_{ser}) increases by 1.89 times when using a CEM II/B cement with a cement strength class (f_{cem}) value about of 42.5 MPa instead of 32.5 MPa [55]. Furthermore, the service life (t_{ser}) increases by 2.49 times when using a water-to-cement ratio (W/C) of about 0.4 instead of 0.43, according to the literature [56]. Previous experimental results [55] [56] have confirmed that service life (t_{ser}) is more sensitive to cement strength class (f_{cem}) and water-to-cement ratio (W/C). In addition, a survey of the literature also reveals that the carbonation resistance of concrete depends on the amount of Portland clinker cement in concrete [57]. When using a cement preparation containing more Portland clinker for concrete composition, first, the 28-day compressive strength of concrete (f_c) is higher and the amount of $Ca(OH)_2$ and CSH increases [58]. Both observations increase concrete carbonation resistance. Finally, the other technological parameters considered here demonstrate a negligible contribution to the variations of service life (t_{ser}). An increase in cement content (C), obviously causes the presence of higher amounts of Calcium hydroxide ($Ca(OH)_2$) and Calcium-Silicate-Hydrate (CSH) inside the concrete, which lengthens the time of the neutralization reaction between $Ca(OH)_2$ and CSH and CO_2. The carbonation resistance is thus higher. An increase in maximum aggregate size (S_max) generates a decrease in the carbonation resistance. The use of a bigger aggregate size, indeed, induces (i) a reduction in the tortuosity of the flow path, which increases permeability, and (ii) a possibility of internal water bleeding, which increases concrete porosity [59]. As regards the initial curing period (t_c), many previous studies [56] [60] [41] have underlined that the longer the curing period is, the higher the resistance of concrete to carbonation is. An increase in t_c provides a higher degree of hydration and a lower concrete porosity. As regards the concrete cover depth (d), it is widely accepted that service life (t_{ser}) is proportional to the square of concrete cover depth (d) as shown in *Eq. (8)*. An increase in sand-to-gravel ratio (S/G) in one cubic meter of concrete mixed increases sand content, which is responsible for the reduction in air permeability. There also, the carbonation resistance is increased [59].

As regards the environmental parameters, previous experimental results [23] [24] have shown that the highest carbonation rate is observed for a relative external humidity (RH) around 57%. We observe that the carbonation rate increases when relative external humidity (RH) increases from 0% to 57%, and decreases when relative external humidity (RH) increases from 57% to 100%. This is consistent and corresponds to the highest σ_j/μ_j^* of relative external humidity (RH) (*Figure 4*) that is highlighted by the present sensitivity analysis results. The carbonation rate also increases with increasing ambient temperature (T) due to increased molecular activity [61] [62]. Finally, the carbonation depth is proportional to the square root of carbon dioxide concentration in the air (CO_2) (*Eq. (7)*). The presence of carbon dioxide is necessary for the carbonation of concrete. However, relative external humidity (RH) and ambient temperature (T) play the most important part in the carbonation rate within all the environmental parameters.

The influence trend of parameters is consistent with the literature. The important influence of parameters corresponding to their range variation studied corroborates with previous experimental studies.

3.4. Final design

Based on the SA results, the action levers of the case study are cement strength class (f_{cem}), water-to-cement ratio (W/C) and cement type (CEM). The final design is carried out by setting the action lever at their most favorable value to increase the service life (t_{ser}) (*Table 2*). As found previously, the most favorable values of the three action levers consist of minimum W/C (about 0.4), higher f_{cem} 52.5 MPa and CEM I or CEM II/B cement type (*Figure 5*). The other parameters are randomly generated according to their PDF presented in *Table 1*. This scenario is called *recommended scenario*.

A reference scenario, called *EN 206-1 scenario*, is also developed by setting the action levers at the limiting values recommended by EN 206-1 [15], i.e., W/C equal to 0.5, f_{cem} 32.5 MPa and CEM I cement type (*Table 2*). The other parameters are randomly generated according to their PDF as with the *recommended scenario*.

We compare the distribution of t_{ser} of *EN 206-1 scenario* and *recommended scenario* with CEM I cement type in *Figure 6*. The *recommended scenario* with CEM II/B cement type is not illustrated in *Figure 6* as its t_{ser} distribution is very close to that of CEM I cement type. The mean t_{ser} of *recommended scenario* with CEM II/B cement type is of about 9,253 years. The distribution of t_{ser} is simulated using a Monte Carlo simulation with a sample size of 100,000.

Table 2. Values of action levers for both designed scenarios.

Parameter	Symbol	Unit	Recommended scenario	EN 206-1 scenario
Water-to-cement ratio	W/C	n.u.	0.4	0.5
Cement strength class	f_{cem}	MPa	52.5	32.5
Cement type	CEM	n.u.	CEM I	CEM I

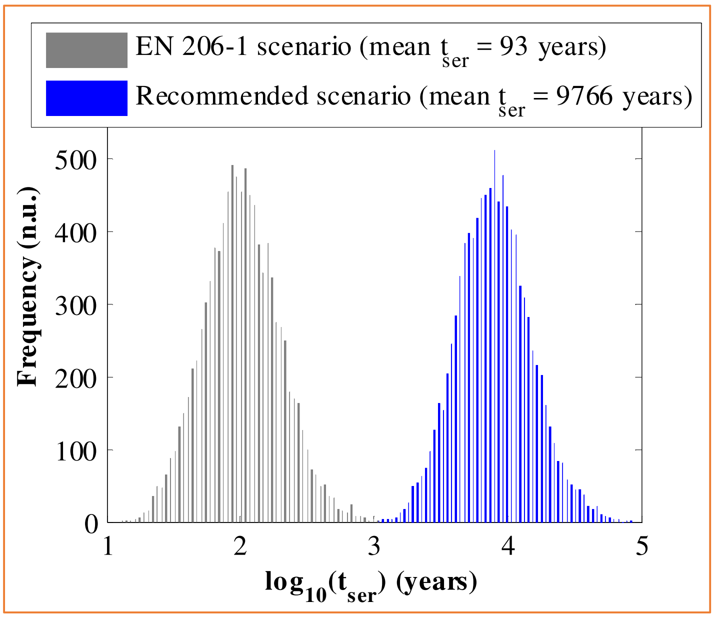

Figure 6. Comparison between service life (t_{ser}) distributions of both designed scenarios.

As shown in *Figure 6*, the t_{ser} of the *recommended scenario* is 105 times higher than that of the *EN 206-1 scenario*. Both distributions of probabilities are completely separated. The calculated differences are significant. The simulation results confirmed f_{cem}, W/C as being effective action levers. The *recommended scenario* corresponds to concrete with higher carbonation resistance. We consider the high concrete cover depth (d) between 0.05 m and 0.08 m, that is another reason for finding the mean service life of the *recommended scenario* of about 9,766 years. This finding corroborates with previously experimental results [4] [34] [35] [36]. For example, Houst et al. [34] reveal that more than five years of exposure to the atmosphere of CO_2, concrete with W/C = 0.3 is carbonated only to a depth of 0.2 to 0.3 mm. Another study on ultra-high performance fiber-reinforced concrete (porosity about 5%) [63] shows that the t_{ser} is more than 12,000 years. One can assume that this higher t_{ser} is not only due to the individual influence of action levers but also to the non-negligible interactions between the action levers and other parameters (revealed previously through the differences $S_{T_j} - S_j \geq 10\%$).

The simulation results of the *recommended scenario* reveal that a durable RC structure can be obtained by setting the action levers at their most favorable values. The durable RC structure is independent on the values of the other technological parameters, which are simulated randomly within their variability range given in *Table 1*. In short, if the RC structure is designed using the *recommended scenario*, the risk for corrosion of reinforcing steels due to carbonation is eliminated throughout the 100-year service life design. In addition, concretes with f_{cem} 52.5MPa and with W/C of about 0.4 are appropriate for the other cement types (*Figure 5*). On the contrary, if the RC structure is designed by setting the action levers at their limiting values as recommended by EN 206-1 [15], a maintenance system could be established in order to ensure the intended 100-year service life.

3.5. Advantages and limits of the design approach

In this particular case, the cement content (C) does not individually contribute to service life (with S_j around 1%), i.e., the service life (t_{ser}) is independent of cement content (C) for a given water-to-cement ratio (W/C). A previous study has revealed that the carbonation of concrete is independent of cement content (C) (from 221 to 450 kg/m^3) for a given water-to-cement ratio (W/C) [64]. The present finding, achieved in association with the literature, raises the problem of attempting to impose a minimum cement content (C) of 300 kg/m^3 for XC4 exposure class in EN 206-1 [15]. The model developed does not consider that a high cement content (C) may enhance the risk of cracking because of the heat of hydration or the drying shrinkage in the concrete cover. Both can result in a poor carbonation resistance of the concrete cover. Furthermore, from the point of view of the environmental impacts of the concrete, cement, among other constituents of concrete, is mainly responsible for the release of a huge amount of CO_2 during the production [65]. Consequently, in the case of an XC4 exposure class, the requirement for the minimum C in EN 206-1 [15] should be re-examined whereas a maximum limit of C within the mix should also be specified.

Our approach is a helpful tool in the life cycle design for the durability of RC structures. Our approach aims identifying action levers for increasing service life. Engineering designers easily increase the service life by focusing on effective action levers.

Results of our case study are related both to the carbonation model chosen and to PDF of input parameters. If we use another range variability of input parameters, our results would be changed [66]. However, our approach is general and can be adapted to various service life models.

In this study, carbonation is the only alteration phenomenon of RC structure that is considered. However, concrete carbonation can be coupled with other severe deteriorations leading to accelerate its degradation, e.g., the presence of a small amount of chlorides significantly increases the corrosion risk in carbonated mortars [67]. In that situation, the combined effects of various alteration mechanisms integrated in service life model.

Finally, this study focuses on individual input parameters that are action levers on the improvement of service life of RC structures. However, interactions between two or more input parameters were shown to be also influential on service life prediction and merit further investigations.

4. Summary and conclusion

The present study was conducted to develop a new design procedure for the durability of RC structures through resistance to carbonation induced corrosion. This innovative approach consists in combining the techniques of the prescriptive and performance-based approaches and in integrating the sensitivity analysis of service life in the design stage. The durability design phase has focused on the most influential parameters with a view to setting them at their most favorable value. With suitable calculation tools, this proposed procedure will be easy to use by designers.

Through the case study presented here, we found that cement strength class (f_{cem}), water-to-cement ratio (W/C) and cement type (CEM) are action levers. Design engineers may take these action levers carefully into account during the durability design step of concrete exposed to carbonation. When setting the action levers at their most favorable values instead of their limiting values as recommended by EN 206-1, the service life is significantly improved. The requirement for minimum cement content (C) in EN 206-1 for XC4 exposure class should be re-examined in order to reduce concrete costs and environmental impacts. The most influential parameters, including W/C, f_{cem}, CEM, ambient temperature (T) and relative external humidity (RH), should therefore be carefully considered in future research works conducted to address the problem of carbonation-induced corrosion damage modeling in RC structures.

More research work needs to be carried out to investigate the interaction influences between the parameters. For instance, in the case study presented, the identified action levers have strong interactions with the other parameters. These interactions, however, have not been examined here. The results of studies addressing the problem of interactions between parameters could additionally enhance the durability of RC structures. We are confident that this finding will serve as a basis for future theoretical and experimental works.

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Appendix: Definitions

Durability is the ability to maintain the serviceability of a structure over a specified length of time, or a characteristic of the structure to function for a given period with required safety and corresponding characteristics providing serviceability [68].

Durability design makes sure that service life design can be completed in the actual local exposure conditions during the design stage.

Service life design is the service life that the designer intends for the structures undergoing expected aggressions and service maintenance according to a prescribed maintenance management strategy.

Service life is the period after construction, during which all the structure properties, when routinely maintained, are higher than the minimum acceptable values [2].

Technological parameters are controllable parameters (i.e. action possibilities). They are related to the technological aspects (e.g., concrete mix, size of structure).

Environmental parameters are uncontrollable parameters. They are related to the environmental open-air location (e.g., aggressive agent sources like CO_2 concentration, chlorides, ambient temperature, and relative humidity).

Action levers are the technological parameter, which are major contributors to the sensitive service life. They are determined by carrying out a sensitivity analysis of the service life prediction model.

Table A1. Cement type characterization.

Cement type	Clinker (n.u.)	CaO (n.u.)	Cement density (kg/m^3)
CEM I	0.98	0.64	3110

CEM II/A	0.87	0.62	3000
CEM II/B	0.72	0.46	3005
CEM III/A	0.5	0.53	2880
CEM III/B	0.27	0.48	2850
CEM III/C	0.12	0.46	2750
CEM IV/A	0.77	0.38	2980
CEM IV/B	0.55	0.31	2890
CEM V/A	0.52	0.47	2870
CEM V/B	0.3	0.47	2870