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Durability and Cover Depth Provisions in Next Eurocode 2. Background Modelling and Calculations

Capítulo sobre durabilidad y recubrimientos en el próximo Eurocódigo 2. Documento de fundamentos y cálculos

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ABSTRACT

Codes contain calculation rules of general acceptance that have demonstrated to enable building safe enough structures with very low probability of failure. Any new method to be introduced, should be based on a consensus among experts and based on the experience. Until now, the durability is treated in the Codes following the so called "prescriptive" approach that is based on selection of constituents and limiting values of their mix-proportions or the characteristic strength, applying a correct curing limiting the presence of deleterious substances such as chlorides and crack widths in serviceability conditions, according to exposure classes. The paper describes the changes introduced in the durability verification in the revision of EN 1992-1-1:2004 currently under formal adoption. The main change is an attempt to design for durability using a performance based approach based on calculating the cover values that avoid reinforcement corrosion. These values were calculated using service life models. The covers are given in function of the "Exposure Resistance classes (ERC)" which substitute current "structural classes". The calculations are not explicit in the Code, because they do not intrinsically imply a higher precision, but only a more rationale and harmonization. The paper also presents the definition and scope of the ERC's which will be regulated in a new standard to be named: EN206-100. The current method in EN-206 to verify durability (reproduced in Annex P of the current draft of FprEN 1992-1-1:2023) will be retained for a transition period and it could continue to be applied with acceptable confidence depending on the provisions valid in the place of use. The ERC's approach is different and its coherence with the present one in EN206 (Annex P) cannot be guaranteed, but the application of one or other route pretends to provide the desired level of durability.

KEYWORDS: Codes, durability, performance, exposure resistance classes, cover depth.

RESUMEN

Los códigos contienen reglas de cálculo de aceptación general que han demostrado permitir la construcción de estructuras lo suficientemente seguras con muy baja probabilidad de fallo. Cualquier nuevo método que se introduzca, debe basarse en un consenso entre expertos y en la experiencia. Hasta el presente, la durabilidad es tratada en las Normas siguiendo el llamado enfoque "prescriptivo," que se basa en la limitación de los constituyentes del hormigón o su resistencia a compresión, mediante aplicación de un curado correcto y limitación la presencia de sustancias nocivas como los cloruros y de la fisuración relacionada con las condiciones de servicio, en función de las clases de exposición. En el artículo se describen los cambios introducidos en la comprobación de la durabilidad en el nuevo borrador actual de EN -UNE 1992-1-1:2004. Los principales cambios se basan en un primer intento de hacer el cálculo de los recubrimientos a través de un enfoque prestacional a través de modelos de vida útil. Los recubrimientos se especifican en función de un nuevo concepto: las clases de resistencia al ambiente, (ERC), que sustituyen a las actuales "clases estructurales". Los cálculos no se explicitan en el Código, porque no implican intrínsecamente una mayor precisión, sino más racionalidad y armonización. En el documento también se presenta la definición y el alcance de las ERC que se regularán en un próximo borrador de norma denominada: EN206-100. El método actual para verificar la durabilidad como se indica en la presente EN-206 (reproducido en el Anejo P del borrador actual de la

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FprEN 1992-1-1-2023), se mantendrá durante un período de transición y podrá seguir siendo aplicado. Dado que el nuevo método que introduce las ERC se basa en un nuevo enfoque y formato de seguridad, no se puede garantizar la coherencia con el método anterior, pero la aplicación de una u otra vía dará el nivel de durabilidad deseado.

PALABRAS CLAVE: Códigos, durabilidad, prestaciones, clases-de-resistencia-al-ambiente, recubrimientos.

1. INTRODUCTION

The codes on structural concrete contain a set of rules that ensure a level of safety that the experience shows is adequate, as shown by the fact that accidents during construction or use are very rare, showing the very low probability of failure. The duration of the structure in absence of deterioration, without major repair works, during a predefined period of time is called then "service life" (as the serviceability limit states are fulfilled). Experience on durability has shown that it is not adequate in certain exposure conditions if the cover depths or the construction quality are deficient. It is now when codes are trying to incorporate modern methods to calculate service life based on what is termed a "performance approach", that is, not specifying the material composition, but the material performance. The reason of the delay in incorporating the modelling of the service life in codes is based on the lack of enough experience and calibration of these models, because codes should only incorporate what is proved and enables sufficiently reliable predictions.

Durability prescriptions in current codes are quite basic. They are focused on specifying cover depths as a function of the exposure classes with the simultaneous limitation in each of the following magnitudes:

- the maximum amount of w/c ratio and the minimum value of cement
- alternatively, the minimum concrete strength
- application of a sufficiently long curing regime
- limiting the chloride content in the raw materials used to manufacture concrete
- the maximum crack width in serviceability conditions

The cover depths are aligned with the limitation of the concrete mix proportions or its characteristic strength and the maximum crack width as a function of the aggressivity of the environment. These prescriptions are described in chapter 4 of current EN-1992-1-1:2004 [1] under the heading of "Durability" and EN 206 [2] Annex F.

The draft of the new version of EC2, FprEN-1992-1-1:2023 [3] contains certain evolution towards a performance-based methodology for durability aspects. The main differences are related to that the cover depths were deduced from model calculations, although all models used are valid and the final cover depths proposed were adjusted for a rationale with respect to the classes (ERC's). This is precisely due to uncertainties in the adequate input parameters for each case and doubts as whether the input data could be generalized. In the new circulated draft for voting [3], durability prescriptions are in chapter 6 instead of chapter 4 [1]. The fact that service life models [5-9] have been used (the calculations are given in the Background Document [10] for Chapter 6) does not imply a higher precision, but a more rational approach and greater harmonization. The resulting cover depths have been agreed through the use of four different service life models and they are given in Tables 6.3 and 6.4 of the new document [3].

The major change in this new draft is not that such cover depths are calculated through a service life model, but that they are given as a function of a new concept: the exposure resistance classes (ERC) [3,10-11] which substitute the current "structural classes" [1]. They are a way of classifying the expected durability of the concrete mixes. In the current draft the concept is only applied for carbonation and chloride attack to the reinforcement. All other degradation processes continue with the prescriptive approach since background knowledge for modelling these processes is still not fully developed. The durability provisions are defined including a certain period of corrosion propagation within the 50 or 100 years service life; meanwhile, the ERCs correspond to a probability lower than 90% of an unacceptable level of carbonation or chloride ingress under standardized exposure conditions. It is necessary to complement such long-term requirement (performance) with the ones to be fulfilled when the concrete is prepared. Thus, the values of the carbonation rate and of chloride diffusion coefficient to comply with by the concrete specimens at 28 days are now conforming a document which is named EN 206-100 [11] (it is not still finished when writing this paper) that will contain the values to be fulfilled by the specimens for each ERC.

It is worth noting, that although general durability principles are mandatory for all EU members, final NDP (National Determined Parameters) may be adjusted or calibrated by national standardization committees in each country as desired.

This paper briefly describes the changes introduced in the new draft of Eurocode-2, FprEN 1992-1-1:2023 [3] and in the EN 206-100 [11] (not definitively approved) related to durability aspects. The paper is structured according to the following list of contents:

1. Deterioration processes due to environmental actions
2. Table of Exposure classes
3. Concept of ERC's
4. Cover depths: Calculation procedure from models of service life (contained in the Background Document)
5. Cover depths for stainless steel reinforcements
6. Content of EN 206-100
7. Final comments.

2. DETERIORATION PROCESSES DUE TO ENVIRONMENTAL ACTIONS

Although not providing provisions for all of them, Chapter 6 of new draft of FprEN1992-1-1:2023 [3] lists the concrete

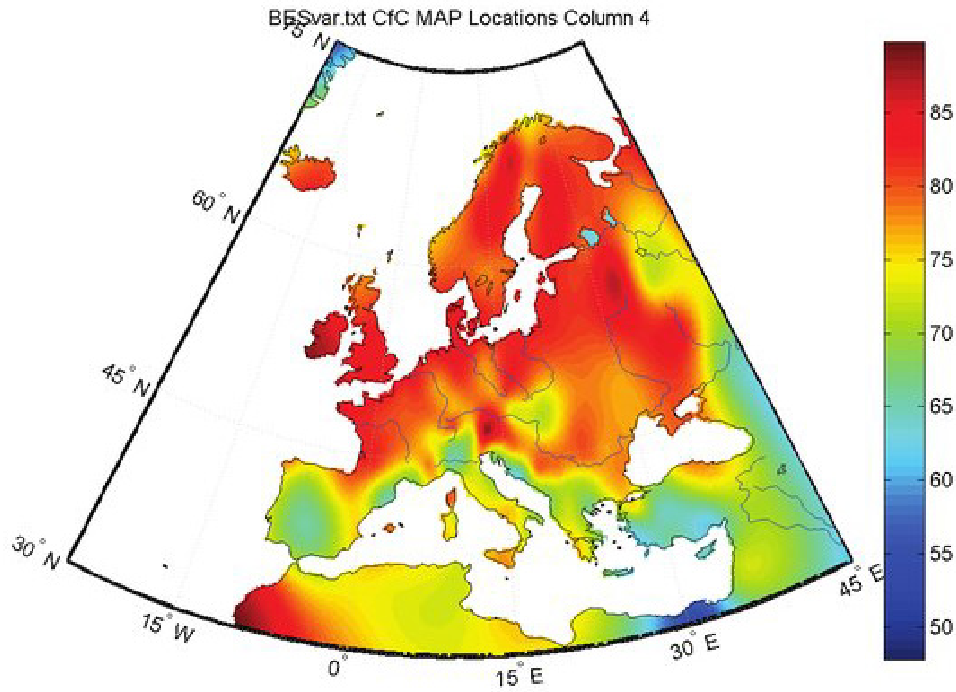

Figure 1. Mean annual external relative humidity [%] [13].

and environmental exposure conditions that may lead into deterioration. The list is the following:

- alkali-aggregate reaction (AA);
- biological attacks arising from e.g.:
  - algae;
  - vegetation;
- chemical attacks arising from e.g. the use of the structure (storage of liquids, etc.):
  - acid solutions;
  - soft water;
  - sulfates;
  - other chemicals;
- delayed ettringite formation (DEF);
- physical attack, arising from e.g.:
  - abrasion;
  - temperature change (including freeze/thaw);
  - water penetration;
- reinforcement corrosion due to carbonation or chlorides ingress;
- reinforcement corrosion that may be due to chlorides present in concrete before exposure;
- stress corrosion cracking.

3. TABLE OF EXPOSURE CLASSES

The new draft provides an updated table of the Exposure classes for reinforcement corrosion. This is shown in Table 1 (Table 6.1 in [3]). The table of other types of attack is not reproduced because it remains essentially unchanged, with only the abrasion classes included. The exposure classes for reinforcement corrosion are the same as in the previous version except for the definition of XC1 and XC2. Now XC1 is "dry" conditions alone and not "dry and wet". The reason for this superseded "dry and wet" classification is because the classes attended to ease of carbonation and they are the conditions where carbonation is minimal or is not produced (wet) and therefore, they were grouped in a single class. However, now the basis for the classification is the risk of corrosion and therefore, the grouping has changed because the carbonation in itself is not considered the limit. The adopted threshold is the corrosion of the reinforcement. Thus, now the risk of corrosion is negligible if the concrete is dry but not, if the concrete is wet. The wet conditions are now under the heading of XC2, XC3 represents the case of concrete exposed to the atmosphere but protected from rain, while XC4 is exposed to rain and with cyclic wet-dry periods.

During internal coordination meetings some doubts arose on how to define XC3 and XC4 exposure. The reason was the mean annual external relative humidity. Northern European countries consider XC3 / XC4 ambient with an average relative humidity of 80 – 85%, southern countries consider values around 65 – 70% (see Figure 1), providing quite different criteria for a durability approach, especially on corrosion onset and propagation [12-13]. These specific topics shall be addressed in NDPs for affected Countries.

4. CONCEPT OF ERC'S

In the current version EN 1992-1-1:2004 [1], the structural classes (from S1 to S6 Table 4.4N and 4.5N) are the intermediate step to select the cover thickness (Table 2). These structural classes have been a concept not fully defined and in

TABLE 1.
Exposure classes related to environmental conditions named Table 6.1 in present draft of [3].

Class	Description of the environment	Informative examples where exposure classes may occur (NDP)
1. No risk of corrosion or attack		
For concrete without reinforcement or embedded metal:		
X0	All exposures except where there is freeze/thaw, abrasion or chemical attack.	Plain concrete members without any reinforcement.
2. Corrosion of embedded metal induced by carbonation		
Where concrete containing steel reinforcement or other embedded metal is exposed to air and moisture, the exposure should be classified as follows:		
XC1	Dry.	Concrete inside buildings with low air humidity, where the corrosion rate will be insignificant.
XC2	Wet or permanent high humidity, rarely dry.	Concrete surfaces subject to long-term water contact or permanently submerged in water or permanently exposed to high humidity; many foundations; water containments (not external). NOTE 1 Leaching could also cause corrosion (see (5), and (6), XA classes).
XC3	Moderate humidity.	Concrete inside buildings with moderate humidity and not permanent high humidity; External concrete sheltered from rain.
XC4	Cyclic wet and dry.	Concrete surfaces subject to cyclic water contact (e.g. external concrete not sheltered from rain as walls and facades).
3. Corrosion of embedded metal induced by chlorides, excluding sea water		
Where concrete containing steel reinforcement or other embedded metal is subject to contact with water containing chlorides, including de-icing salts, from sources other than from sea water, the exposure should be classified as follows:		
XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides.
XD2	Wet, rarely dry.	Swimming pools; Concrete components exposed to industrial waters containing chlorides. NOTE 2 If the chloride content of the water is sufficiently low then XD1 applies.
XD3	Cyclic wet and dry.	Parts of bridges exposed to water containing chlorides; Concrete roads, pavements and car park slabs in areas where de-icing agents are frequently used.
4. Corrosion of embedded metal induced by chlorides from sea water		
Where concrete containing steel reinforcement or other embedded metal is subject to contact with chlorides from sea water or air carrying salt originating from sea water, the exposure should be classified as follows:		
XS1	Exposed to airborne salt but not in direct contact with sea water.	Structures near to or on the coast.
XS2	Permanently submerged.	Parts of marine structures and structures in seawater.
XS3	Tidal, splash and spray zones.	Parts of marine structures and structures temporarily or permanently directly over sea water.

absence of a precise definition the recommendation was to use the class S4. The exposure resistance classes are a substitution of such structural classes with a more coherent concept behind them, as they are defined to classify the concrete mixes by their durability, measured in specimens in the short term, from carbonation or chloride tests after 28 days of standard curing.

TABLE 2.
Values of minimum cover,cmin,dur requirements with regard to durability for reinforcement steel in accordance with EN 1991-1-1: 2004 [1].

Environmental Requirement for $c_{min,dur}$ (mm)							
Structural Class	Exposure Class according to Table 4.1						
	X0	XC1	XC2/XC3	XC4	XD1/XS1	XD2/XS2	XD3/XS3
S1	10	10	10	15	20	25	30
S2	10	10	15	20	25	30	35
S3	10	10	20	25	30	35	40
S4	10	15	25	30	35	40	45
S5	15	20	30	35	40	45	50
S6	20	25	35	40	45	50	55

Because of the lack of agreed models [9] for other than carbonation and chloride ingress, the ERC concept only has been applied to these two deterioration mechanisms. They have been defined by committee TC250/SC2/WG1/TG10: Durability [10] and expressed in [3] of which, both authors of the paper have been members. The definitions were very much discussed and although not all members fully agreed, they were approved by a majority of the TG10 members. The definition agreed upon was:

- Carbonation: *XRC classes for resistance against corrosion induced by carbonation are derived from the carbonation depth [mm] (characteristic value 90% fractile) assumed to be obtained after 50 years under reference conditions (400 ppm CO_2 in a constant 65%-RH environment and at 20 °C). The designation value of XRC has the dimension of a carbonation rate [mm/$\sqrt{(years)}$].*
- Chloride ingress: *XRDS classes for resistance against corrosion induced by chloride ingress are derived from the depth of chlorides penetration [mm] (characteristic value 90% fractile), corresponding to a reference chloride concentration*

(0,6% by mass of binder (cement + type II additions)), assumed to be obtained after 50 years on a concrete exposed to one-sided penetration of reference seawater (30 g/l NaCl) at 20 °C. The designation value of XRDS has the dimension of a diffusion coefficient [10^{-13} m²/s].

The main aspects considered in relation these definitions it has to be added:

- The performance is defined for a service life of 50 years, although cover depths for 100 years also are given.
- The service life includes a certain level of corrosion attack (initiation and propagation periods) complied with 90% of probability.
- Although the classification is derived by the depth of carbonation or chloride ingress the units of the ERC's are mm/year$^{0.5}$ for carbonation rate and cm²/s for the diffusion coefficient of chlorides.
- The values are calculated for reference conditions that are translated through each service life model to each exposure class. The reference conditions are:
  - 400 ppm CO_2 in a constant 65% RH environment and at 20°C for carbonation attack
  - reference seawater (30 g/l NaCl) at 20°C for chloride ingress.

The fulfillment of the definitions can be achieved by testing for carbonation or chloride attack or by complying with the future EN 206-100 [11] or with Annex P of [3], which reproduces the current EN 206 [2].

These definitions enable the classification by testing under carbonation or chloride ingress of different mixes. However, testing will not be the only way to fulfil the ERC's [11]. They can be also fulfilled through the concrete composition. This was agreed in the committee to induce a "smooth transition" from current situation, where the approach is fully prescriptive (concrete composition), to the new requirements (performance). Additionally, each country should select the manner of incorporating the new concept into their respective standards. The choices will be described later when explaining the new EN 206-100 (in preparation) [11].

4.1. Denomination of ERC's

The ERC classes finally agreed upon are shown in the first column of Tables 3 (carbonation) and 4 (chlorides) [3,10]. Those of carbonation (XRC) have eight and those of chlorides have ten levels. They can be merged or even split into more (obtained by interpolation) as the national standardization bodies decide based on the national concretes and experience.

It is worth to repeat that the cover depths are a function of the ERC's and of the exposure classes. It should be noted, not to mistake the XRC (exposure resistance to carbonation) with the XC (exposure to carbonation), because the last one is the classification of the aggressivity of the environment while the XRC is the level of resistance to such XC.

5. COVER DEPTHS

Cover depths have been calculated independently using five different service life models in which the input parameters are not identical [10]. The results were however only slightly different because of the selection of different exposure input parameters as mentioned. At the end, the cover depths were then rounded by consensus, based on the experience on the subjects of carbonation and chloride ingress of the persons involved in the calculations [10]. Therefore, the cover depths proposed are not the result of an exact mathematical calculation, but of the application of expert opinion to the calculated values. Because of this, any attempt to reproduce the exact values may fail if the input parameters and the assumptions of each model are not identical to those assumed and specified in the Background document [10]. The agreed cover depths are given in Table 3 for carbonation and Table 4 for chlorides of chapter 6 of [3]. They correspond to the minimum depth which provides the nominal resistance plus an allowance for deviation, Δc_{dev}:

$$c_{nom} = c_{min} + \Delta c_{dev} \tag{1}$$

As is common, the value for c_{min} shall satisfy the requirements for both bond and durability:

$$c_{min} = \max\{c_{min,dur} + \Delta c;\ c_{min,b};\ 10\text{ mm}\} \tag{2}$$

where:

$c_{min,dur}$ minimum cover required for environmental conditions;

Δc sum of the following applicable reductions and additions:

- $\Delta c_{min,30}$ reduction of minimum cover for structures with design life of 30 years or less;
- $\Delta c_{min,exc}$ reduction of minimum cover for superior compaction or improved curing;
- $\Delta c_{min,p}$ additional minimum cover for prestressing tendons;
- $\Delta c_{dur,red}$ reduction of minimum cover for use of additional concrete protection or use of special measures for protection of reinforcing steel;

$\Delta c_{dur,abr}$ additional minimum cover for abrasion;

$c_{min,b}$ minimum cover for bond requirement.

For concrete cast directly against soil surface, the minimum cover should be increased by Δc_{min} considering the increased uncertainty and variability of concrete and the reduced compaction against soil.

5.1. Deterioration (condition) limit state

This new limit state, [7,10,14-15] implicitly introduced into the calculations, has been also incorporated into current draft of *fib* Model Code 2020 [7]. As shown in Figure 2 [10] the deterioration limit state is based on the end of service life not when the chloride threshold is reached or the carbonation front arrives to the external surface of the bar (the nick point in the red curve), but when a certain amount of corrosion is

TABLE 3.
Minimum concrete cover $c_{min,dur}$ for carbon reinforcing steel — Carbonation (Table 6.3 (NDP) of [3]).

ERC	Exposure class (carbonation)							
	XC1		XC2		XC3		XC4	
	Design service life (years)							
	50	100	50	100	50	100	50	100
XRC 0,5	10	10	10	10	10	10	10	10
XRC 1	10	10	10	10	10	15	10	15
XRC 2	10	15	10	15	15	25	15	25
XRC 3	10	15	15	20	20	30	20	30
XRC 4	10	20	15	25	25	35	25	40
XRC 5	15	25	20	30	25	45	30	45
XRC 6	15	25	25	35	35	55	40	55
XRC 7	15	30	25	40	40	60	45	60

NOTE 1 XRC classes for resistance against corrosion induced by carbonation are derived from the carbonation depth [mm] (characteristic value 90% fractile) assumed to be obtained after 50 years under reference conditions (400 ppm CO_2 in a constant 65%-*RH* environment and at 20 °C). The designation value of XRC has the dimension of a carbonation rate [mm/√(years)].

NOTE 2 The recommended minimum concrete cover values $c_{min,dur}$ assume execution and curing according to EN 13670 with at least execution class 2 and curing class 2.

NOTE 3 The minimum covers can be increased by an additional safety element $\Delta c_{dur,\gamma}$ considering special requirements (e.g. more extreme environmental conditions).

TABLE 4.
Minimum concrete cover $c_{min,dur}$ for carbon reinforcing steel — Carbonation (Table 6.3 (NDP) of [3]).

ERC	Exposure class (chlorides)											
	XS1		XS2		XS3		XD1		XD2		XD3	
	Design service life (years)						Design service life (years)					
	50	100	50	100	50	100	50	100	50	100	50	100
XRDS 0,5	20	20	20	30	30	40	20	20	20	30	30	40
XRDS 1	20	25	25	35	35	45	20	25	25	35	35	45
XRDS 1,5	25	30	30	40	40	50	25	30	30	40	40	50
XRDS 2	25	30	35	45	45	55	25	30	35	45	45	55
XRDS 3	30	35	40	50	55	65	30	35	40	50	55	65
XRDS 4	30	40	50	60	60	80	30	40	50	60	60	80
XRDS 5	35	45	60	70	70	—	35	45	60	70	70	—
XRDS 6	40	50	65	80	—	—	40	50	65	80	—	—
XRDS 8	45	55	75	—	—	—	45	55	75	—	—	—
XRDS 10	50	65	80	—	—	—	50	65	80	—	—	—

NOTE 1 XRDS classes for resistance against corrosion induced by chloride ingress are derived from the depth of chlorides penetration [mm] (characteristic value 90% fractile), corresponding to a reference chlorides concentration (0,6% by mass of binder (cement + type II additions)), assumed to be obtained after 50 years on a concrete exposed to one-sided penetration of reference seawater (30 g/l NaCl) at 20 °C. The designation value of XRDS has the dimension of a diffusion coefficient [10^{-13} m^2/s].

NOTE 2 The recommended minimum concrete cover values $c_{min,dur}$ assume execution and curing according to EN 13670 with at least execution class 2 and curing class 2.

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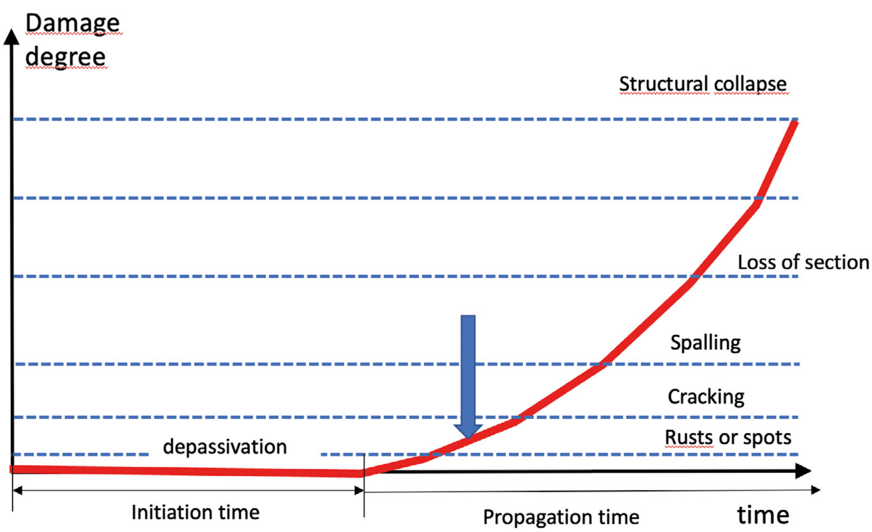

Figure 2. Service life model (Tuutti [5]) that shows with a blue arrow the time corresponding to the deterioration limit state [10,14]: before a crack parallel to the reinforcement appears on the concrete surface.

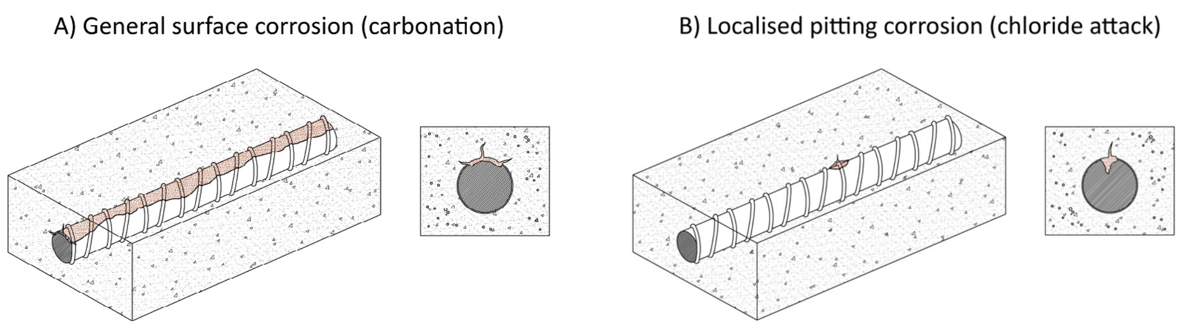

Figure 3. schematic illustration of the limit state of deterioration (condition limit state) regarding general corrosion (carbonation) and regarding localized corrosion (chlorides) [10].

reached (see the blue arrow in Figure 2) [14]. This is because the corrosion onset is not an instant, but it is a period of time in which active corrosion-repassivation may occur and because it is very difficult to identify the moment at which depassivation occurs [15]. However, when the corrosion is active, its identification can be easier from the cracking or rust spots on the outer surface. This new definition of the limit state allows to deal with incongruences generated when thicker covers were required in a dryer environment without causing external damage. A more detailed explanation on this concept can be found in the "introduction" paragraphs of the Background Document [10].

Then, it is only when the corrosion is permanently active that it can be said that the service life foreseen in the design is over. The amount of corrosion that is considered as a limit is 50 µm for general corrosion penetration (carbonation) and of 500 µm for localized attack (pitting) (Figure 3 and 4). These values were adopted by convention and, in reinforced concrete they will affect neither SLS nor ULS. A different case are prestressed steels in which such limits do not apply because smaller corrosion may lead into undesired failure [10,14,15].

The initiation period is modelled by means of diffusion transport models for carbonation and for chloride ingress and then, the design service life is denoted as the sum of the initiation period and the propagation period [5]:

$$t_{SL} = t_{ini} + t_{prop} \tag{3}$$

The duration of the propagation period depends on the exposure, composition of concrete, concrete cover and bar diameter but for the standard, the limit adopted by convention corresponds to the mentioned corrosion induced loss of thickness equal to 50 µm (homogeneous corrosion) and 500 µm (localized corrosion) Figure 4 [3,15].

$$t_{prop} = P_{corr} \,/\, V_{corr} \tag{4}$$

where V_{corr} is the corrosion rate and P_{corr} = 50 µm is the limit value for the average penetration (carbonation-induced corrosion) that is supposed not to cause visible surface cracking. In case of chloride-induced corrosion, pitting depth P_{pit} = 500 µm is deemed to be a lower bound (conservative) estimate of the pitting depth that would not induce cracking in the concrete cover (although P_{pit} up to 1000 µm has been observed without cracking). This pitting depth limit P_{pit} has been allocated on an averaged corrosion depth P_{corr} between 50 mm and 100 mm assuming a pitting factor of 10.

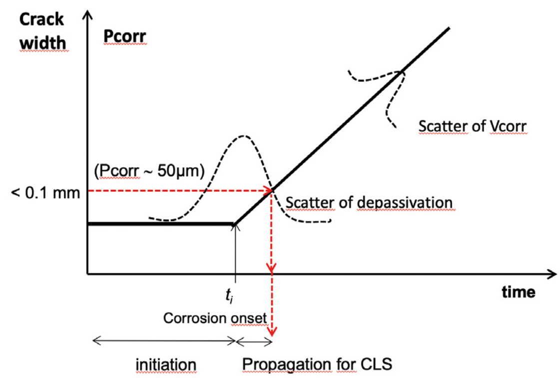

Figure 4. Representation of the Condition/ Deterioration/Corrosion limit state (CLS) [10,14,15]. It means that the service life is not only the initiation period, but also an initial part of the propagation period, that for corrosion is nominally ascribed to a corrosion penetration of P_{corr} =50 µm of averaged uniform corrosion depth, assuming equivalent to have crack widths in the concrete surface smaller than 0.1 mm.

5.2. Reliability associated to the end of design service life

Methods of establishing the reliability may follow the general principles for probabilistic service life design of concrete structures outlined in ISO 2394 [16], EN 1990 [17] and ISO 13823 [18] and, for deterministic calculations or semi-probabilistic approaches, include margins to reach the same target reliability.

The probability of exceeding a given limit state (failure probability) is quantitatively expressed by the reliability index, bi-univocally related to the previous through the cumulative Gauss function:

$$P_f = \Phi^{-1}(-\beta) \tag{5}$$

where

P_f is the failure probability,

Φ^{-1} is the Gauss inverse cumulative distribution and,

β is the reliability index.

The failure probability selected was derived after a benchmark examination of the estimated reliability level for the current design criteria in Spanish code EHE-08 [19] and the German prescription for concrete DIN 1045-1 [20]. The adopted target value was β= 1.5 which corresponds to a nominal probability of 7% as is illustrated in Figures 5 and 6 [21].

Hence, a target value of β=1.5 at a life time of 50 years has been used to elaborate the recommended cover depths, $c_{min,dur}$.

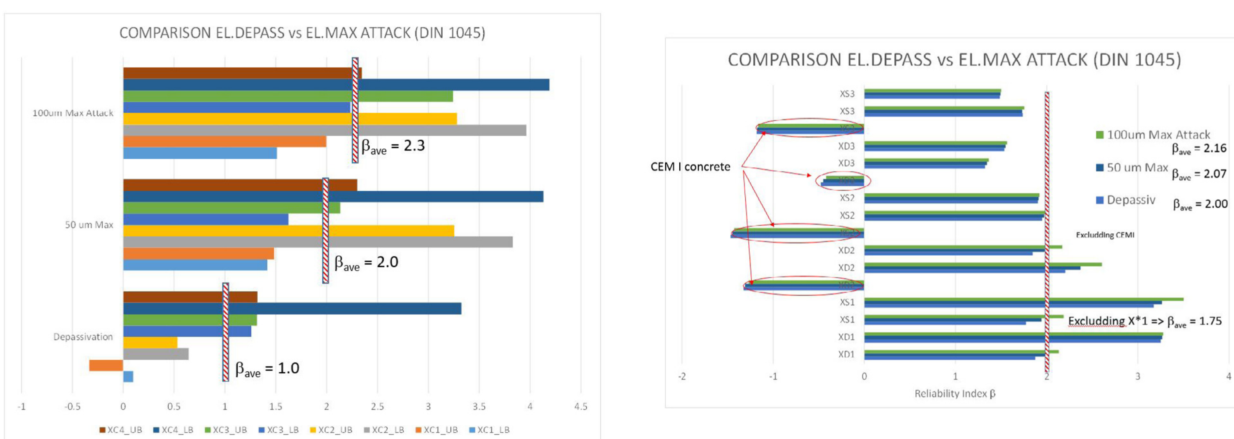

Figure 5. Reliability index for current deemed to satisfy rules in DIN 1045-1 [21] calculated following the procedure of Annex 1 and 2 of present paper. As more positive is the β value, les probability of that the aggressive front reaches the bar position with the cover depths considered in DIN standard. Negative β values indicate probabilities of failure higher than 50%.

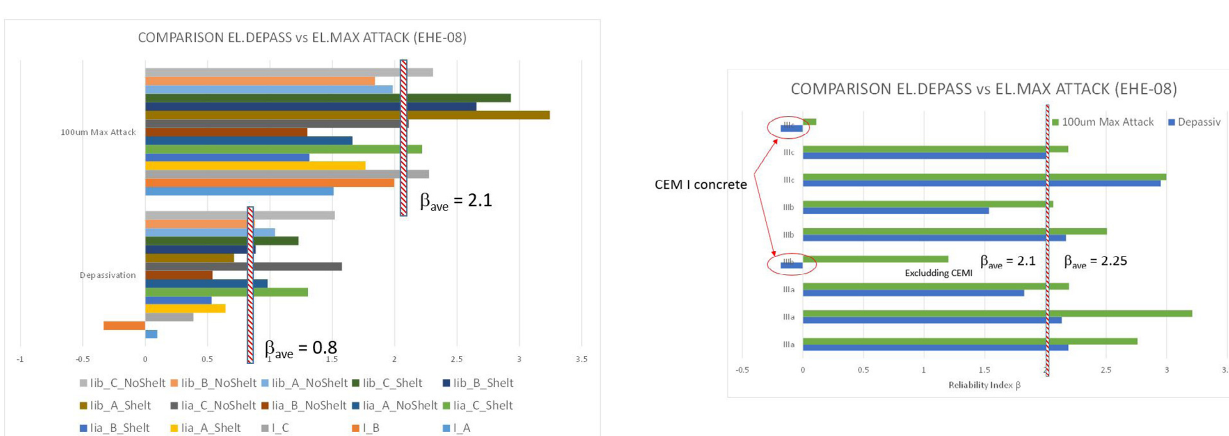

Figure 6. Reliability index for current deemed to satisfy rules in Spanish EHE-08 [21] calculated following the procedure of Annex 1 and 2 of present paper. As more positive is the β value, les probability of that the aggressive front reaches the bar position with the cover depths considered in EHE08 standard. Negative β values indicate probabilities of failure higher than 50%.

This target value β=1.5 represents a failuer probability around 7% for the undesirable event of depassivation of the steel reinforcement followed by a limited part of the propagation period [10,14,15,22,23].

A target reliability of β=1.3 is often used for the depassivation limit state [7,10,14], which is consistent with a slight increase to 1.5 [9] for considering the durability limit state as initiation followed by a certain part of the corrosion phase. This β = 1.5 value was also considered as being compatible with current normally used cover depths [1]. This difference in reliability should be considered when comparison between the cover depths proposed in EC2-draft and other code is made.

A single target value for β has been used for the durability limit state of reinforced concrete structures, without specifically taking account of the ease of access for inspection and maintenance. This level of the reliability index is considered acceptable for most types of concrete structures and components. An additional recommended cover depth has been given for the corrosion of prestressing steel, because of the higher severity of the consequences of failure and differences in the corrosion mechanism. Interpretation in terms of reliability is detailed in a specific chapter. Although the description of the calculation of the failure probabilities may require a dedicated text, a short summary is included in one of the methods used in the Background Document [10] included at the end of this paper as annex 1 and 2.

6. COVER DEPTHS FOR STAINLESS-STEEL REINFORCEMENTS

The use of stainless steel has been introduced with the same rationale as normal steel reinforcements. That is, the cover depths will depend on the ERC's and on the type of steel itself, because not all the stainless steels used as reinforcement have the same resistance against corrosion. Table 5 (Table Q.3 in the draft of FprEN1992-1-1:2023 [3]) shows the cover depths for this type of reinforcements.

7. PROVISIONAL CONTENT OF EN 206-100

The current draft 10 of EN 206-100 [11], submitted to comments and not yet approved, contains mainly:

- The definition of ERC.
- The testing methodology for carbonation and chloride ingress.
- The levels of compliance and assessment of concrete mixes.
- The values of the carbonation rate and chloride diffusion coefficient to comply with each ERC.

TABLE 5.
Minimum concrete cover cmin,dur to stainless steel reinforcement (Table Q.3 (NDP) of [3]).

Exposure Class	Exposure resistance class ERC	Stainless steel resistance class[a]			
		SSRC1	SSRC2	SSRC3	SSRC4
XC1	≤ XRC7	0	0	0	0
XC2		0	0	0	0
XC3	≤ XRC4	0	0	0	0
	≤ XRC7	15	0	0	0
XC4	≤ XRC4	15	0	0	0
	≤ XRC7	20	0	0	0
XD1, XS1	≤ XRDS0,5	10	0	0	0
	≤ XRDS1,5	20	10	0	0
	≤ XRDS3	25	15	10	0
	≤ XRDS6	35	25	15	0
	≤ XRDS10	45	35	25	15
XD2, XD3, XS2, XS3	≤ XRDS0,5	15	10	10	0
	≤ XRDS1,5	25	20	15	0
	≤ XRDS3	35	30	20	10
	≤ XRDS6	50	40	30	20
	≤ XRDS10	65	50	40	30

NOTE 1 The tabulated cover values apply for a design service life of 50 years unless a National Annex excludes some classes or gives other values.

NOTE 2 For a design service life of 100 years $c_{min,dur}$ in Table Q.3 (NDP) should be increased by +10 mm for all ERC classes unless a National Annex excludes some classes or gives other values.

NOTE 3 In case of combined action of carbonation and chloride induced corrosion, $c_{min,dur}$ in Table Q.3 (NDP) should be increased by 20 mm or a higher stainless steel resistance class should be chosen unless a National Annex gives other values.

NOTE 4 As alternative to the class system of Table Q.3 a performance-oriented service life design may be applied if the input parameters out of technical product specifications are available.

[a] For stainless steel corrosion resistance classes see Table Q.2.

ERC's are defined by performance using either (see Figure 7):

- testing, using a European reference test method and criteria given in the standard; or,
- testing, using a European test method or National test method, with criteria specified by provisions valid in the place of use; or,
- limiting values for composition and properties of concrete.

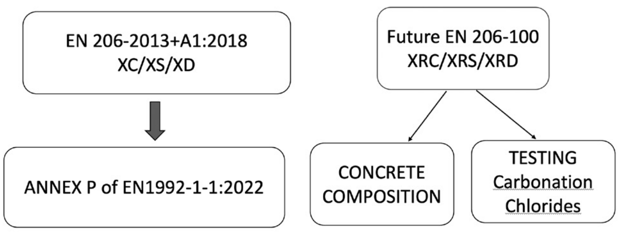

Figure 7. Routes of verifying the XRC's [11].

With the values of each ERC the structure is expected to achieve the design service life provided:

- the appropriate ERCs were selected;
- the concrete has the minimum cover to reinforcement in accordance with FprEN 1992-1-1:2023 [3];
- the concrete is properly placed, compacted and cured, e.g. in accordance with current EN 13670 [24] and EN 13369 [25];
- the appropriate maintenance is applied during the service life.

The standard gives four levels of testing and assessment (Table 6) (Table 1 in the draft of EN206-100) [11]. These levels range from selecting a pre-defined concrete and then accepting that any variability is reliably assessed by the standard EN 206 procedures [11], to specifying standard procedures with additional testing where greater reassurance of constancy of performance is required.

The denomination of ERC is through the letters XRC for carbonation and XRDS for chlorides, both sea water and deicing salts. The letters are followed by a number that represents the classification from more to less resistant to the attack.

7.1. Resistance classes by testing

The preliminary proposal being discussed on Initial type testing ITT, is summarized:

- carbonation classes, XRC, can be verified using the reference test method, EN 12390-10 chamber test [26]. National provisions may use other accelerated carbonation test (EN 12390-12) [27] providing the factor of conversion to natural conditions are given
- chlorides the assessment is made through the reference test method given in EN 12390-11 [28]. The EN 12390-18 chloride migration test [29], or test methods permitted by the provisions valid in the place of use, may be used to define the performance of XRDS concrete with the corresponding factor for natural conditions.

TABLE 6.
Levels of testing and assessment [11] (preliminary proposal not yet approved) (Table 1 in the draft 10 of EN206-100).
***Initial type testing**

Task	Level 0	Level 1	Level 2	Level 3
Initial type testing	Not required[a]	In accordance with 5.2		
Confirmation of ITT*		Every four years[b]	Every four years[b]	Not required[c]
Additional routine testing		As required to confirm that any change in the source of a constituent does not adversely affect durability.	As level 1 plus resistivity as frequently as compressive strength testing.	As level 2 and additional tests The frequency of testing specified in provisions valid in the place of use or as otherwise specified.

[a] Conforming to 4.1 (1) and (2), and limiting values and concrete properties to 4.3
[b] And where there is a significant unexplained change in fresh or hardened concrete properties
[c] May be specified

TABLE 7.
ITT criteria for the XRC classes based on the EN 12390-10 chamber test [26] (Table 4 in draft 11* of EN-206-100)**
***proposed by the CEN/TC104/SC1/WG1/ADG not yet approved**
**** mean values used in the probabilistic calculations of the authors of this paper (see Annex 1)**
***** New draft in discussion**

XRC class	Mean carbonation rate,* mm/√years	Mean carbonation rate in the ITT,** mm/√years
XRC0,5	0.36	0.5
XRC1	0.72	1.0
XRC2	1.44	2.0
XRC3	2.17	3.0
XRC4	2.89	4.0
XRC5	3.61	5.0
XRC6	4.33	6.0
XRC7	5.06	7.0

TABLE 8.
Mean value for the XRDS classes based on the EN 12390-11 diffusion test [28] (named Table 6 in draft 11 of EN-206-100).**
*** proposed by the CEN/TC104/SC1/WG1/ADG not yet approved**
**** New draft in discussion**

XRDS class	Mean diffusion coefficient for various ageing factors, $\times 10^{-12}$ m²/s*			
	$\alpha \geq 0,3$	$\alpha \geq 0,4$	$\alpha \geq 0,5$	$\alpha \geq 0,6$
XRDS 0,5	0.17	0.28	0.47	0.78
XRDS 1	0.34	0.56	0.93	1.56
XRDS 1,5	0.50	0.84	1.40	2.33
XRDS 2	0.67	1.12	1.87	3.11
XRDS 3	1.00	1.68	2.80	4.67
XRDS 4	1.34	2.24	3.73	6.22
XRDS 5	1.68	2.80	4.66	7.78
XRDS 6	2.01	3.35	5.59	9.33
XRDS 8	2.68	4.47	7.46	12.4
XRDS 10	3.51	5.59	9.33	15.6

Where the use of non-reference test to assess the performance of an XRDS concrete is accepted, then all parties should confirm assessment criteria to try and avoid the possibility of dispute if the performance is questioned at a later date.

7.2. Levels of XRC's to comply with

The current tables, not yet approved for carbonation and chlorides, are given in Table 7 (Table 4 in the EN206-100 draft-11) and 8 (Table 6 in the draft-11) (please notice that it is mentioned the draft 11 and not the draft 10 of EN206-100 because the values are in continuous change). They show the preliminary ITT mean value (x_n is the mean value of 3 ITT results) that testing results should comply with.

8. FINAL COMMENTS

The chapter on Durability in EN 1991-1-1 has been renewed more in the fundamentals than in the resulting text. The changed aspects were mainly based on:

- A more rational identification of the possible deterioration processes.
- For the case of reinforcement corrosion, in the calculation of the cover depths through service life models of carbonation and chloride ingress adopting as the onset of corrosion a certain period of propagation, introducing "de facto" a new limit state "condition or deterioration limit state" whose compliance should not affect the serviceability or ultimate limit states. That is, the propagation period allowed should not produce cracks in the cover beyond their value for SLS. This new limit state corrects some anomalies and contradictions caused using the traditional depassivation criterion.
- The introduction of the exposure resistance classes that is a method for ranking the potential durability of the concrete using performance tests in early stages.

The new concept of exposure resistance class defined in the EN206-100 and applicable to concrete mixes, enables to rank their expected durability and link it to the cover depths. This is expected to contribute to the introduction of new types of binders, very demanded for the goal of concrete decarbonation.

A final comment is that the new concrete classification should be used it its own, because it is based on different safety criteria and concepts than current codes. The old and new concepts should not be mixed. Thus use: a) current EN 206-2013+A1:2018 (referred to in Annex P in FprEN1992-1-1:2023) [2] or alternatively b) the new FprEN1992-1-1:2023 (chapter 6) [3] and EN 206-100 [11]. The mixing or comparison of both systems may lead into erroneous or incoherent results. Concrete producers deciding to fit into the new system should work on adjusting their concrete mix proportions to the ERC's, with independence of the current EN 1991-1-1:2004.

Acknowledgements

The authors would like to recognize the interesting contributions of several members of the European committees CEN/TC250/SC2/WG1/TG10 and CEN/TC104/SC1/WG1 and also are grateful to the centers they were or are members of (IETcc: Institute of Construction Sciences- CSIC-Spain, CIMNE and the UPM: Polytechnical University of Madrid) for the permission for attending the volunteer work that standardization always represents.

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[28] CEN (2015) EN 12390-11 Testing hardened concrete - Part 11: Determination of the chloride resistance of concrete, unidirectional diffusion

[29] CEN (2021) EN 12390-18 Testing hardened concrete - Part 18: Determination of the chloride migration coefficient.

ANNEXES: CALCULATIONS SUPPORTING THE COVER DEPTHS GIVEN IN F*prEN1992-1-1:2023*

As mentioned in chapter 4 of present paper cover depths given in Tables 3 and 4 have been independently calculated by several members of the CEN/TC250/SC2/WG1/TG10 using different service life models, in which the input parameters are not identical [10]. These calculations are incorporated into the Background Document of Chapter 6 of FprEN 1992-1-1:2023.

Next as Annexes 1 and 2 are reproduced the chapters 2.2 (carbonation) and 3.2 (chlorides) prepared by the authors of present paper to that Background Document. The models used for the calculations have been in fib Model Code (MC2010) and in JCSS Probabilistic Model Code. Each Annex has the corresponding bibliography used for their preparation.

These Annexes have not been reviewed for present paper and are exclusive responsibility of the authors. The numbering of the chapters is the original of the Background Document mentioned.

ANNEX 1

BACKGROUND DOCUMENT

CHAPTER 2.2
Carbonation induced corrosion
By David IZQUIERDO and Carmen ANDRADE

2.2.1 Objective

The objective of present document consists in establishing the cover depths for 50 and 100 years that fulfil the definition of the exposure resistance classes (ERC) given in chapter 1.2.6. Additionally, it has been calculated the values of the ERC designations at short term (V_{CO_2}) coherent with those values for the case at 50 years.

For achieving that objective, the steps followed are:

- Time-explicit mathematical models for calculating the progress of the carbonation front, and of the corrosion propagation phase, are selected.
- A corrosion propagation period is added to the initiation one in such a length that no external damage is detected in the concrete surface. This assumption makes the service life to be composed of an initiation (t_i) period and a propagation (t_p) one:

  $t_{SL} = t_i + t_p$ *Eq. 2.2.1*

  The definition of the end of service life is shown in Figure 1.1.
- Probabilistic characterization of the input parameters of the models selected
- Formulation of the limit state function (LSF) in which the adequate cover depth is higher than the initiation plus the corresponding propagation periods.
- Selection of the reliability level of compliance of the LSF. In present document the reliability factor b=1.5 has been adopted.
- Calculation of the cover depths complying with the ranking of ERC defined in the chapter 1.2.6 and final proposal of the c_{mim} by subtracting 10 mm.

- Rounding of the cover thickness values in order to fit into stepped round values.

Additionally, calculations were repeated with other probabilistic methods as well as deterministic calculation in order to check whether the values of cover depth are the same or they depend on the calculation method.
Finally, for the objective of the back-extrapolation at short term the same methodology has been followed with the difference of calculating the V_{CO2} instead of the cover thickness.

2.2.1 Carbonation induced corrosion

_2.2.1.1._ Model of the initiation period
For the carbonation model that included in the *fib* MC2010 [*fib* Model Code 2010] has been simplified by "embodying" the input parameters in a smaller number of them. That is the model is reduced to a "square root" one as it is a full simplification, in which all the input parameters, except logically that of the lifetime, are embodied in velocity of carbonation V_{CO2} [Izquierdo 2001]. This simplification is made in order to avoid the need to calibrate the six variables of *fib* carbonation model whose uncertainty and statistical distributions are unknown.

The *fib* model of carbonation [MC2010, *fib* Bulletin 34, Gehlen 2000, Izquierdo 2001] is the following:

$$x_c = \sqrt{2\, k_e\, k_c\, \frac{D_{CO_2}}{a}} \left(\frac{t_0}{t}\right)^w = \sqrt{\frac{2\, k_e\, k_c}{R_{carb}}} \left(\frac{t_0}{t}\right)^w \qquad \text{Eq. 2.2.2}$$

x_c = carbonation depth [mm]
k_e = environmental parameter
k_c = factor for curing regime
D_{CO_2} = diffusion coefficient of carbon dioxide
a = reactive alkaline material in the concrete
t_0 = time were testing is started
t = design service life
R_{carb} = Inverse effective carbonation resistance of concrete
w =wetness factor

This expression is reduced by assuming:

$$V_{CO_2} = \sqrt{\frac{2\, k_e\, k_c}{R_{carb}}} \left(\frac{t_0}{t}\right)^w \qquad \text{Eq. 2.2.3}$$

V_{CO_2} rate of carbonation
Equation 2.2.2. can yield to the following simplified equation
In the case that the k_e, k_c, t_0 and w are set to=1, V_{CO_2} is coincident with the average value of the designation number of the XRC.

$$x_c = V_{CO_2}\, t^{\frac{1-2w}{2}} \qquad \text{Eq. 2.2.4}$$

Considering the time to depassivation as the independent variable:

$$t_{dep} = \left(\frac{c}{V_{CO_2}}\right)^{\frac{2}{(1-2w)}} \qquad \text{Eq. 2.2.5}$$

c = depth of carbonation
The rate of carbonation will be ranked following the ERC's.

2.2.1.1 Input Parameters of the carbonation model and their statistical characterization

2.2.1.1.1 Values of V_{CO_2} and their coefficient of variation (CoV)

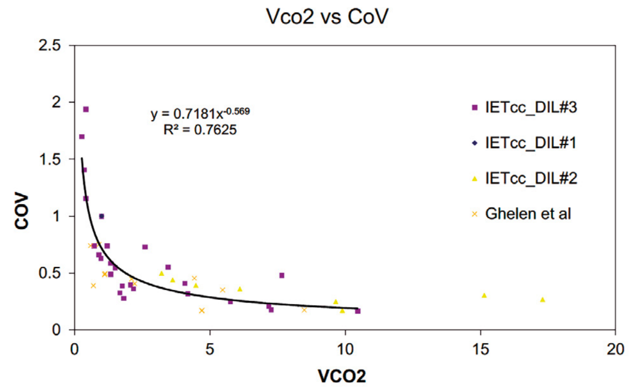

Figure 2.2.1. Relationship between averaged carbonation rate Vco2 and its Coefficient of Variation (expressed as percent per one, thus 1= 100% variation) measured in real structures.

Regarding the CoV of the carbonation rate in tests performed in real structures [Izquierdo 2001, Gehlen 2000] enable to deduce the relationship between average value of carbonation depth and the measured scatter (CoV) when measured in the same zone. The relation between averaged value of the carbonation rate and its scatter is shown in Figure 2.2.1. The CoV is larger logically as smaller is the value, being above 100% (higher than 1 in the figure) for the very low values.

2.2.2.1.1.2 Wetness factor "w" and its CoV
The wetness factor "w" represents the effect of direct rain into the concrete surface [Gehlen 2000] and the delay of the carbonation due to this surface wetness. Eq. 2.2.6 provides its expression:

$$W = \frac{(p_{SR}\, ToW)^{b_w}}{2} \qquad \text{Eq. 2.2.6}$$

where p_{SR} is probability of driving rain and b_w is an exponent of regression [*fib* Bulletin 34, MC2010, Gehlen 2000].

In order to have an order of magnitude of the scatter (in terms of CoV) due to it is not provided in the MC2010, it has been made a Montecarlo simulation whose result is shown in Figure 2.2.2. It shows the values distribution shape and expected coefficient of variation, depending on average value of w.
For each exposure class, input values for w and variation coefficient are shown in Table.2.2.1:

TABLE 2.2.1.
Values of the time of Wetness (averaged per year) and their Coefficient of Variation for the assumptions of exposure classes with averaged low (LH) and high (HH) relative humidities.

Exposure[1]	W_μ	CoV (%)
XC1	0	0
XC2	0.4	6.2
XC3_LH	0	0
XC3_HH	0	0
XC4_LH	0.15	65
XC4_HH	0.24	25

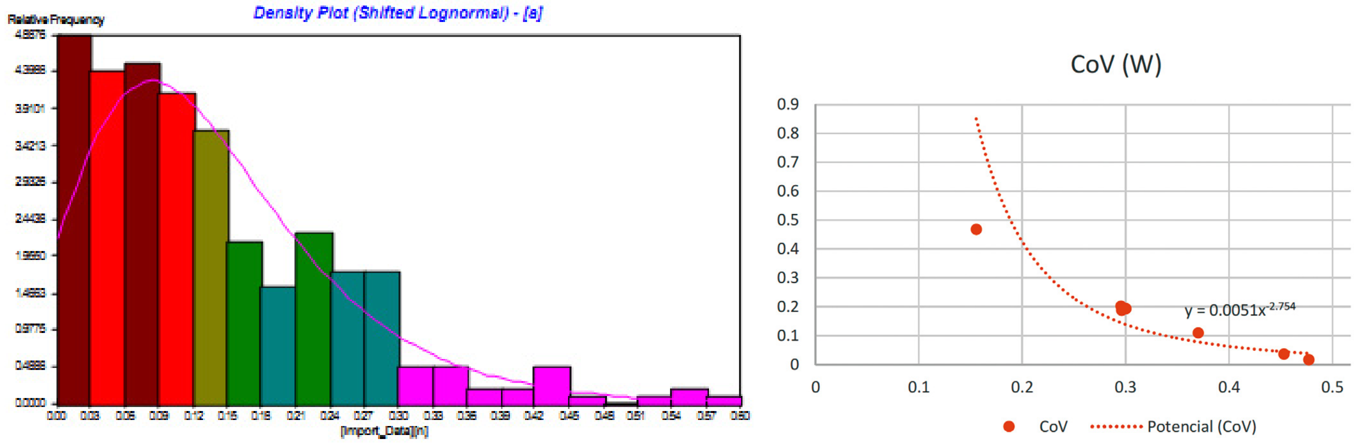

Figure 2.2.2 Left: Distribution values of values of *w* (value of w in X axis and number of simulations in Y axis). Right Values of *w* (X axis) from the simulation (coefficient of variation as percent per one in Y axis).

LH accounts for low humidity conditions (e.g.: 65%RH) and HH accounts for high humidity (e.g.: 75%RH).

2.2.2.1.1.3 Environmental parameter k_e

The parameter k_e in equation 2.2.3 can be calculated through Eq.2.2.7 being *f*=5 *and* g=2.5 obtained from regression analysis [Izquierdo 2001]. However as shown in the Figure 2.2.3 the fitting is not good and then, in Table 2.2.2 are given values calculated from the equation 2.2.7 but assuming average values of RH in each exposure class obtained from the meteorological information in different climates.

$$K_e = \left[\frac{1-\left(\frac{RH}{100}\right)^f}{1-\left(\frac{65}{100}\right)^f}\right]^g \qquad \text{Eq. 2.2.7}$$

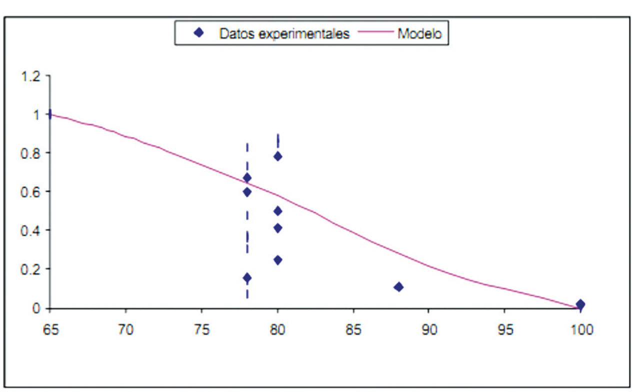

Figure 2.2.3 Fitting of Eq. 8 into values of environmental parameter in real structures The Y axis is the probability and the X axis is the RH.

Table 2.2.2
Values of the environmental parameter in function of the averaged RH obtained from meteorological information for each exposure class

Parameter	XC1	XC2	XC3		XC4	
RH (%)*	65	85	65	75	65	75
k_e	1	0.4	1	0.75	1	0.75

2.2.2.1.1.4. Summary of input parameters of initiation of carbonation

They are given in Table 2.2.3

Table 2.2.3 Summary of the parameters used in the carbonation model

Symbol	Parameter	Units	Equation	Distribution
V_{CO2}	Velocity of carbonation	[mm/Year ^0.5]	$V_{CO_2} = \sqrt{\frac{2\,k_e\,k_c}{R_{carb}}}\left(\frac{t_0}{t}\right)^w$	Log-Nor
W(t)	Wetness factor	[days]	$W = \frac{(p_{SR}\;ToW)^{bw}}{2}$	D
k_e	environmental function	[-]	$K_e = \left[\frac{1-\left(\frac{RH}{100}\right)^f}{1-\left(\frac{65}{100}\right)^f}\right]^g$	Calculated for average RH values

2.2.2.2. Model for calculation the corrosion propagation

The corrosion rate V_{corr} is assumed to be constant (averaged annually) and then, the propagation model is given by [Andrade et al. 1989, Andrade 2019]:

$$t_{pro} = \frac{(\phi_0 - \phi_t)}{V_{corr}} = \frac{p_{corr}}{V_{corr}} \qquad \text{Eq. 2.2.8}$$

where t_p is the corrosion propagation time in years, ϕ_0 is the initial diameter of the bar in mm and f_t is the remaining diameter after corrosion in mm, P_{corr} (mm) is the accumulated corrosion or penetration of attack after a certain period of time and V_{corr} (mm/year) is the annually averaged corrosion rate.

The calculations were made considering the end of service life as described in the chapter 1.2.3 when a P_{corr} = 50 µm for homogeneous corrosion as expected in carbonated structures.

2.2.2.2.1 Input Parameters of the propagation model and their statistical characterization

For propagation period, and following principles shown in [Andrade et al 1989, Andrade 1998, Contecvet 2001, Duracrete 2000, Andrade 2020] values are given in Table 2.2.4.

TABLE 2.2.4.
Values of the corrosion rate adopted in the exposure classes and their corresponding *CoV*.

Exposure	V_{corr} [mm/y]	CoV (%)	$V_{corr,d}$ c=1,5	t_{pro} [yr] β=1,5
XC1	1	65	2.0	25
XC2	4	65	5.4	9
XC3	2	65	4.0	13
XC4	5	90	12.9	4

V_{corr} is the average corrosion rate in the particular exposure class
CoV is the assumed coefficient of variation
$V_{cor,d}$ is the design value of the corrosion rate calculated through Eq. 2.2.17
t_{pro} is the propagation period calculated through Eq. 2.2.16.

For scatter quantification, after [Izquierdo 2001], it can be shown that 60% of variation can be expected for those exposure cases with *constant* conditions (e.g.: XC1/XC2/XC3) for all other cases 90% to 120% of variation is used.

2.2.3. Formulation of Limit State Function

The probabilistic and partial factor methodology used next are those of the Probabilistic Model Code of the JCSS (Joint Committee of Structural Safety).

The Limit State considered is mathematically expressed as the probability that the corrosion depth at the time of the Design Service Life (DSL) is smaller than the P_{max} (50µm):

$$P_X\,(t_{DSL}) \leq P_{max} \qquad \text{Eq. 2.2.9}$$

This eq. can be rewritten in terms of Limit State function G(·) as:

$$G\,(t) = P_{max} - P_X\,(t_{DSL}) \qquad \text{Eq. 2.2.10}$$

where
$P_X\,(t_{DSL})$ is the achieved corrosion degree at the end of the design service life:

$$P_X\,(t) = \begin{cases} 0 & \text{if } t \leq t_{dep} \\ V_{corr}\,(t - V_{corr}) & \text{otherwise} \end{cases} \qquad \text{Eq. 2.2.11}$$

V_{corr} is the corrosion rate (µm/y)
V_{corr} is the depassivation time

Depassivation and corrosion rate will be different for each exposure class as per EN206, as well as its respective mathematical expressions (as indicated in Table 2.2.4).

2.2.3.1 Reliability analysis and method

In order to calculate the probability of P_x being higher of P_{max} a whole probabilistic analysis can be performed, however for this calibration the suggested procedure by EN1990:2002 or the previous background document [annex C prEN 1990-2:2020]. This procedure is based on the determination of *design point*, which is the *most probable combination of variables that provokes reaching limit state*, see figure 2.2.4.

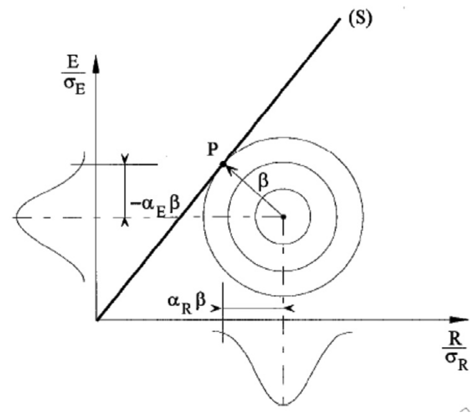

Figure 2.2.4. Design point and reliability index beta according to FROM method for Normally dstributed variables.

Where: (S) is the failure boundary g = R – E = $P_{max} - P_x$
(P) is the design point
The design value for every variable can be calculated such that the probability of having more unfavourable values is as follows:

$$X_d = X^* = F^{-1}\,(-\alpha\beta) \qquad \text{Eq. 2.2.12}$$

Where α's are the values of the FORM sensitivity factors. The value of a is negative for unfavourable variables (*actions*) and positive for favourable variables (*resistances*). Following from FORM probabilistic method, it can be shown that:

$$\Sigma\alpha^2 = 1 \qquad \text{Eq. 2.2.13}$$

In case of multivariate analysis and for calibration purposes [annex C prEN 1990-2:2020] the following values of Table 2.2.5 can be adopted:

TABLE 2.2.5.
Values of sensitivity factors of resistance and action variables.

Resistance Variables		Action Variables	
Leading	a = 0.70	Leading	a = -0.80
Accompanying	a = 0.28	Accompanying	a = -0.32

For calibration purposes only simplified distributions will be adopted: Normal, log-normal, uniform, exponential.

2.2.3.2 Sensitivity factors

A full probabilistic study was carried out with all described values during the TC250/SC2/WG1/TG10 work calibrating present Deemed-to-Satisfy rules in Germany and Spain in order to obtain sensitivity factors, and target – reliability values [Izquierdo 2001]. Conclusions from this study in terms of sensitivity factors is as follows:
For the case of carbonation induced corrosion, *resistance variable* is essentially *concrete cover (C)* whereas *action variable* is *corrosion rate* (V_{corr}) calculated values of a's are shown in 2.2 5.

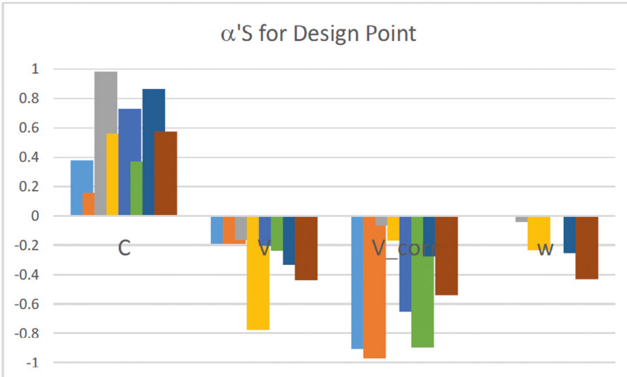

Figure 2.2.5 Sensitivity factor for Carbonation induced corrosion (max. 50um loss of rebar section).

Thus, following from this analysis, following values will be adopted for concrete cover calculation:

TABLE 2.2.6.
Sensitivity factors adopted in the carbonation calculations

Variable	Name	a	Type
Cover	C	0.8	Resistance
Carbonation rate	V_{CO2}	-0.32	Action
Corrosion rate	V_{Corr}	-0.70	Action
Wetness factor	w	0.28	Resistance

It can be easily deduced from the table that $\sum\alpha > 1$ (app. 1.32) what implies that followed approach is slightly conservative. If a further refinement would be required, reported values for a could be divided by $\sum\alpha$ in order to normalize the values. However, for this application and in order to follow EN1990 procedure, no normalization was adopted.

2.2.4 Design values

2.2.4.1 Design values for propagation period

Since the definition of service life is now composed of initiation + propagation periods and because the concrete cover is only affecting the first one, it is necessary to calculate first the propagation period:

$$t_{dep}\,(cover) = service\ life - t_{prop} \qquad \text{Eq. 2.2.14}$$

Therefore, design values for several reliability levels shall be obtained for propagation period. Applying design values to Eq. 2.2.14, yields:

$$t_{dep,d}\,(cover) = service\ life - t_{prop,d} \qquad \text{Eq. 2.2.15}$$

This can be easily made considering a log-normal distribution, 50µm as maximum rebar loss in Eq. 2.2.8 above together with the a values provided in previous Table 2.2.6:

$$t_{prop,d} = \frac{50}{V_{corr,d}} \qquad \text{Eq. 2.2.14}$$

Where $V_{corr,d}$ can be calculated as [annex C prEN 1990-2:2020, Tanner et al. 2019]:

$$V_{corr,d} = V_{corr,\mu}\, e^{\frac{0.70}{0.30}\beta\, Cov} \qquad \text{Eq. 2.2.17}$$

Where α = –0.70 is adopted for XC cases and -0.30 for XS cases. Derived values for corrosion rate and propagation period in years, were given in Table 2.2.4.

It has to be emphasized, the importance of adequate calculation of the propagation period at national or local level, providing its impact in the initiation period.

2.2.4.2. Cover depths for Carbonation induced corrosion

As per agreement in the TC250/SC2/WG1/TG10, results will be presented in terms of the mean carbonation rate in constant chamber conditions (k_e = w = k_c = 1) for a value of reliability index of 1.50. The values in Table 2.2.7 are given in terms of cmin,dur (where 10 mm for tolerance is subtracted from the calculated design value of concrete cover).

Following table 2.2.8 shows obtained crude values (in mm) for 50 yrs for reliability indexes of β = 1, to 1.5 and 2. These values shall be truncated by the minimum cover for other requirements such as anchorage or construction (e.g: 10 mm).

TABLE 2.2.7.
Values of cmin,dur obtained from the design calculated values by subtracting 10 mm.

K	XC1	XC2	XC3_LH	XC3_HH	XC4_LH	XC4_HH
			β = 1,5			
XRC 0.5	0	0	0	0	0	0
XRC 1	0	0	0	0	1	0
XRC 2	0	0	7	6	8	1
XRC 3	1	0	14	13	14	5
XRC 4	4	0	22	20	20	8
XRC 5	8	0	29	26	26	12
XRC 6	11	0	36	33	32	15
XRC 7	14	0	43	40	38	19
			β = 2,0			
K	XC1	XC2	XC3_LH	XC3_HH	XC4_LH	XC4_HH
XRC 0.5	0	0	0	0	3	2
XRC 1	0	0	3	2	7	3
XRC 2	2	0	13	11	15	7
XRC 3	7	0	22	19	23	11
XRC 4	13	0	32	27	31	15
XRC 5	18	1	41	35	38	19
XRC 6	24	2	50	43	46	23
XRC 7	29	4	59	51	53	27
			β = 2,5			
K	XC1	XC2	XC3_LH	XC3_HH	XC4_LH	XC4_HH
XRC 0.5	0	3	1	1	14	13
XRC 1	0	0	8	6	17	11
XRC 2	5	1	20	17	26	15
XRC 3	12	2	32	27	36	20
XRC 4	19	4	44	37	46	25
XRC 5	26	6	56	47	55	30
XRC 6	33	7	67	56	65	35
XRC 7	40	9	79	66	74	40

Table 2.2.8.
Rounded values of $c_{min,dur}$ for 50 and 100 years for β=1.5

Exposure class	XC 1		XC 2 low HR (65%)		XC 3				XC 4			
					High HR (75%)		Low HR (65%)		High HR (75%)			
Design Service life (years)	50	100	50	100	50	100	50	100	50	100	50	100
XRC 0.5	10	10	10	10	10	10	10	10	10	15	10	10
XRC 1	10	10	10	10	10	10	10	10	10	20	10	10
XRC 2	10	20	10	10	15	20	15	15	15	25	10	20
XRC 3	10	20	10	10	20	35	20	25	25	35	10	25
XRC 4	15	30	10	10	35	45	25	35	30	45	15	35
XRC 5	20	35	10	10	40			45	35		20	45
XRC 7	25		10									

Rounded values of $c_{min,dur}$ are given in Table 2.2.8.

2.2.6 References Carbonation

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ANNEX 2

BACKGROUND DOCUMENT

CHAPTER 3.2 - CHLORIDE INDUCED CORROSION

3.2.1 Objective

The objective of present document consists in establishing the cover depths for 50 and 100 years that fulfil the definition of the Exposure Resistance Classes (ERC) given in chapter 1 in the Introduction. For that objective the principles given in the Probabilistic Model Code of the JCSS and the carbonation model of the fib MC2010 have been used.
For achieving that objective, the steps followed are:

- Description of the Time-explicit mathematical model used for calculating the service life to fulfil the definition of ERC
- Phases of the model and selected input parameters
- Statistical characterization of the input parameters.
- Formulation of the Limit state function (LSF). Reliability level of compliance of the LSF. In present document the reliability factor b=1.5 has been adopted.
- Probabilistic calculations of the cover depths complying with the ranking of ERC defined in the chapter 1 of Introduction.

3.2.2 *Chloride induced corrosion*

3.2.1.1 Model the initiation period in marine environments

The time explicit chloride model selected is that of fib MC2010. It is based on the classical 2nd Ficks law with time variant diffusion coefficient and a skin zone Dx. Hence, the chloride concentration at a depth x can be calculated through:

$$C\,(x,t) = C_0 + (C_s - C_0)\left[1-\mathrm{erf}\left(\frac{x-\Delta x}{2\sqrt{D_{ap}\,(t)\,t}}\right)\right] \qquad \textit{Eq. 3.2.1}$$

Where:

C_0 is the initial chloride concentration of chloride in concrete in %

C_S is the concentration at the surface (a fitted value not a real one)

erf is the error function

$D_{app}(t)$ is the apparent diffusion coefficient for chlorides at time t, which usually is estimated with Eq. 3.2.2:

$$D_{ap}\,(t) = D_0\left(\frac{t_0}{t}\right)^n \qquad \textit{Eq. 3.2.1}$$

Where:

t_0 is the reference time for D_{app} evaluation and,

n is the so-called ageing factor, that accounts for the apparent decrement of D_{app} with time.

Probabilistic evaluation of all the input parameters in Eq. 3.2.1 is complex, since a total number of 5 variables has to be calibrated in a posterior analysis. The equation is then simplified as was made that of the carbonation model by embodying several parameters in the velocity of chloride ingress, VCl. The rearranged equation supposes the following mathematical change of variables:

Being the C_{cr} the critical chloride content (in %) it can be used to define the variable ξ:

$$\xi = \frac{C_{cr} - C_0}{C_s - C_0} \qquad \textit{Eq. 3.2.3}$$

and then,

$$V_{cl}\,(t) = erf^{-1}\,(1-\xi)\left[2\sqrt{D\,(t_0)\,(t_0)^n}\right] \qquad \textit{Eq. 3.2.4}$$

In consequence the time to depassivation can be calculated as

$$t_{dep} = \left(\frac{C-\Delta x}{C_{Cl}(t)}\right)^{\frac{2}{1-n}} \qquad \textit{Eq. 3.2.5}$$

For calculation, all scatter is merged into V_{cl} and n in order to make calibration easier and feasible.

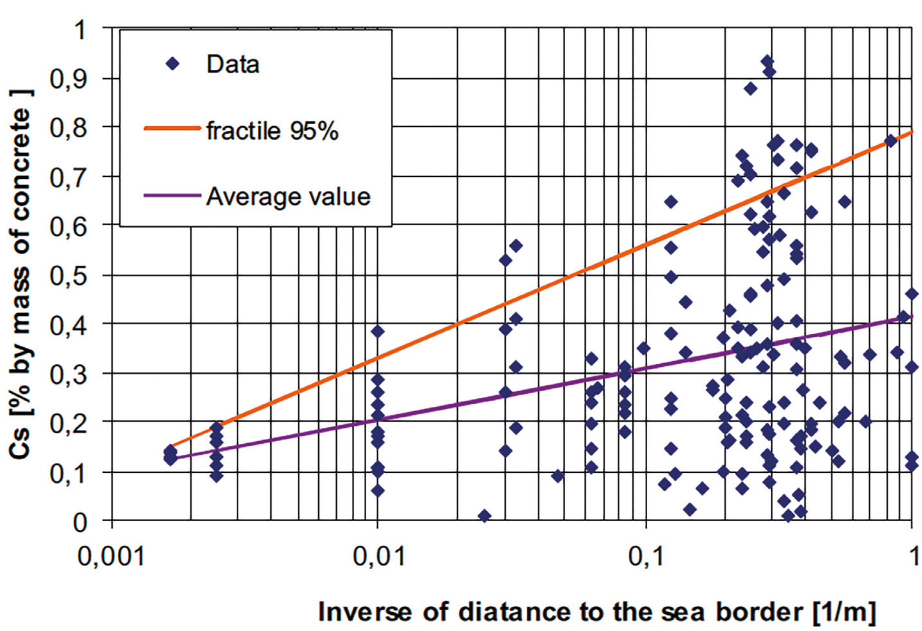

Figure 3.2.1. Relation between distance to shoreline and superficial concentration of chlorides (the X axis shows the inverse to the distance to the seashore).

3.2.2.1.1 Input parameters of the chloride model and their statistical characterization

It consists of calculating or adopting the coefficient of variation to be applicable to each mean value of the input parameter. Calculations are made based on mean values.

3.2.2.1.1.1 Surface chloride concentration

For XS2 and XS3 classes the chloride surface concentration is made to depend on the cement type (Izquierdo, D. Andrade, C., 2011) and ((*fib*), 2015).

TABLE 3.2.1.
Values of the surface concentration in function of cement type considered in the calculations for XS2 and XS3.

Cement type	C_s [%Con]
CEM I	0.35
CEM III/B	0.35
CEM II/A-V	0.55
CEM II/A-D	0.50

For exposure case XS1, surface concentration is dependent on many parameters (seashore distance, height of exposure, wind direction, wave height, etc.). In Figure 3.2.1 are shown the data used for the calculation of the scatter and due to it a simplified ranking approximation was made (Izquierdo, D. Andrade, C., 2011).

The exposure class XS1 is not defined in detail in the EN206 and in reality covers a wide range of distances and locations with respect to the shoreline. For the sake of this exercise a value of 100 m is adopted and therefore average value of 0.2% by weight of concrete of surface chloride concentration with respect to the concrete mass is taken for the calculations.

A CoV = 50% was taken in all exposure classes.

3.2.2.1.1.2 *Critical chloride content* (C_{cr})

Critical chloride content is widely characterized in the literature (Izquierdo et al. 2004). In present calculations an averaged value of C_{cr} = 0.6% by cement weight and a CoV = 30% are adopted, with a normal distribution.

3.2.2.1.1.3. Ageing factor n

Ageing factor is in many cases the most influencing variable in Eq. 3.2.1. Hence a proper calibration of this variable is essential. For this exercise several data sources have been used in order to account for the longest exposure periods because at short periods the aging factor *n* may be still evolving and then, with a high uncertainty. In Table 3.2.2 is provided the values considered and their bibliographic source, together with the CoV recorded.

These data enabled to propose in all cases a CoV = 20% (upper boundary of recorded values) for being adopted in the calculations.

TABLE 3.2.2.
Values of aging factors used in the calculations and references.

Cem type	Source	n_μ (XS2/XS3)	n_μ (XS1)
CEM I	((*fib*), 2015), (Izquierdo, D. Andrade, C., 2011), (Polder, R.B. Rooij, M.R., 2005)	0.45	0.60
CEM II/A-V	(Izquierdo, D. Andrade, C., 2011), (Polder, R.B. Rooij, M.R., 2005)	0.80	0.60
CEM III/B	((*fib*), 2015), (Polder, R.B. Rooij, M.R., 2005)	0.50	0.70
CEM II/A-D	((*fib*), 2015)	0.40	0.65

3.2.2.1.1.4 Skin zone (Δx)

It is named "convection zone" in MC2010, however the mechanisms acting are not only convention and then in preset exercise will be named "skin zone". It is considered only in XS3 environment, where it has been shown that the combination of carbonation and chloride ingress more often leads to a non-fickian diffusion profile (with a maximum in the interior of the concrete). For the calculations, an average value of 10 mm ((*fib*), 2015) and CoV = 50% were adopted.

3.2.2.1.1.5 Chloride velocity V_{Cl} *(t)*

The simplified Eq. 3.2.5 embodying several input parameters and resulting in a V_{Cl} is used for the calculations.

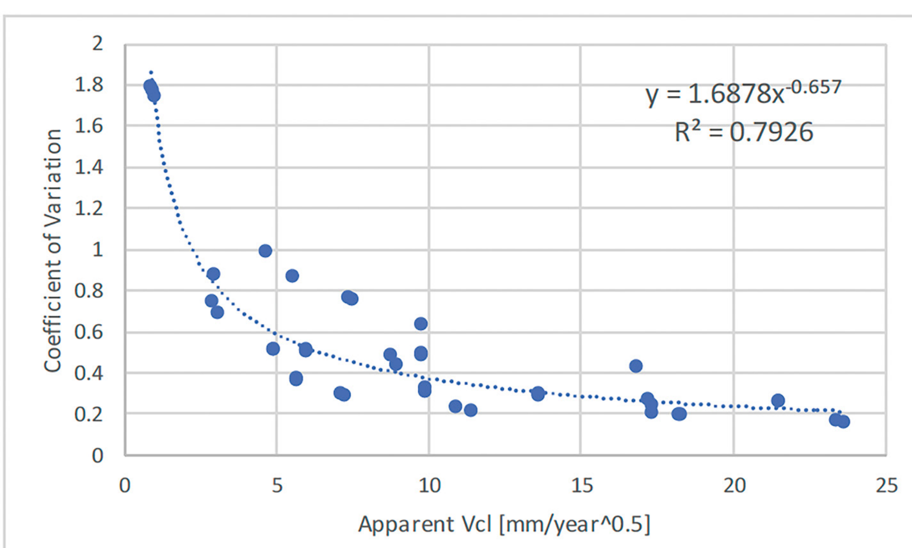

Figure 3.2.2. Average and CoV for apparent chloride ingress rate.

Chloride ingress is dependent of cement type, exposure conditions and concrete quality and then in a parallel manner than in the case of the carbonation rate, the VCl value has been found to depend on its average values, as shown in Figure 3.2.2. It is a hyperbolic function whose formula will be used in the calculations for the CoV.

$$CoV_{VCl} = 1.6878\ C_{Cl}^{-0.657} \qquad \textit{Eq. 3.2.6}$$

3.2.2.1.1.6. Concrete cover

The same CoV = 30% than in chapter 2.2 for carbonation is adopted in present calculations ((*fib*), 2015) (Izquierdo, D. Andrade, C., 2011) (Izquierdo. D, 2001).

Table 3.2.3 .
Adopted Coefficient of variation of the concrete cover thickness.

Type of execution	Dist. Type	Bias	CoV
in situ – normal conditions	Log-normal	1.0	30%
Precast – dedicated quality control	Normal	1.0	10%

3.2.3.2 Summary of input parameters of initiation of corrosion due to chloride ingress

TABLE 3.2.4.
Input parameters for the chloride modelling.

Parameter	Units	Average value	CoV (%)	Statistical distribution
C_0	[wt.-%/cem]	0.01	20	Log-Nor
$C_{s,Dx}$	[wt.-%/conc]	See Table 3.2.1 for XS2/XS3 And 0.2% for XS1	50	Log-Nor
C_{crit}	[wt.-%/conc]	0.1	30	Normal
Dx	[mm]	10mm only in XS3	50	D
c	[mm]	several	30	See Table 3.2.3
V_{Cl}	[m²/Ös]	several	See equation 3.2.5	Log-Nor
n	[-]	See Table 3.2.2.	30	
t_0	[years]	28 days	-	-
t	[years]	50 and 100 years	-	-

3.2.2.2 Model of the propagation period

The propagation model is the same than for carbonation described in (Andrade 1989):

$$t_{pro} = \frac{P_{corr}}{V_{corr}} \qquad \textit{Eq. 3.2.6}$$

where t_p is the corrosion propagation time in years, P_{corr} (μm) is the accumulated corrosion or attack penetration after a certain period of time and V_{corr} (μm/year) is the annually averaged corrosion rate.

3.2.2.2.1. Input Parameters of the propagation period and their statistical characterization

For propagation period, the values considered taken are those given in Table 3.2.5 (Andrade, C., 1999). For scatter quantification, after (Izquierdo, D. Andrade, C., 2011), it was obtained that 60% of CoV variation is shown in exposure cases with constant conditions (e.g.: XS1/XS2) and 90% in XS3 with wet-dry cycles.

Table 3.2.5.
Values of the corrosion rate adopted in exposure class and their corresponding CoV. Propagation periods until Pcorr = 500 μm.

Exposure	V_{corr} [μm/y]	CoV (%)	$V_{corr,D}$ b=1,5	t_p[yr] b=1,5
XS1	30	60	56.3	1
XS2	10	60	13.1	4
XS3	70	90	105.0	0

3.2.2.3 Service life model

The service life is composed of an initiation (t_i) period and a propagation (t_p) one:

$$t_{SL} = t_i + t_p \qquad \textit{Eq. 3.2.7}$$

3.2.3. Formulation of Limit State Function

The probabilistic and partial factor methodology used next are those recommended in the Probabilistic Model Code of the JCSS.

The method is the same than that described in chapter 2.2.3 for carbonation

3.2.3.1 Sensitivity factors

Sensitivity factors and target – reliability values (Izquierdo, 2019) have been calculated for the input parameters of the model. The results obtained are the following:

a) For the case of chloride induced corrosion (seawater source), the sensitivity factors are shown in Figure 3.2.3 can be deduced that, on the resistance side Cover and ageing factors are leading values, whereas chloride ingress rate (V_{Cl}) is the leading variable on the action side.

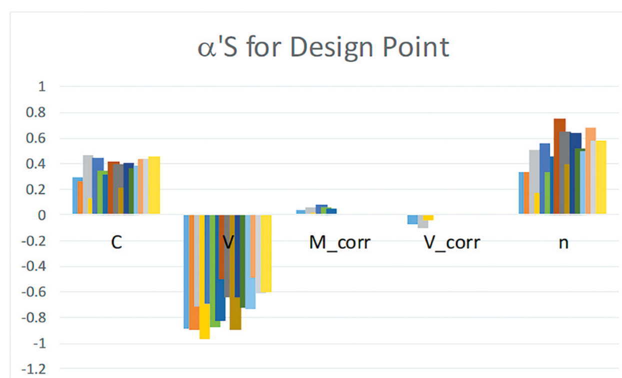

Figure 3.2.3. Sensitivity factors for Chloride induced corrosion (max. 50μm loss of rebar section).

For calculation purposes the parameters given in Table 3.2.6 are adopted.

TABLE 3.2.6.
Sensitivity factors of the input service life parameters in the case of carbonation

Variable	Name	a	Type
Cover	C	0.40	Resistance
Chloride Ingress rate	V_{Cl}	-0.80	Action
Corrosion rate	V_{Corr}	~0	Action
Ageing factor	n	0.60	Resistance

In the same manner than in the case of carbonation, the summatory $\sum\alpha > 1$, that implies that the values are slightly con-

TABLE 3.2.7. Calculated minimum values (10 mm were subtracted from the nominal cover used in the calculations) for 50 and 100 years of service life)

Calculated mínimum cover depths						
b=1.50	XS1		XS2		XS3	
	50 years	100 years	50 years	100 years	50 years	100 years
XRD 0.5	16.0	18.1	19.0	24.7	32.0	37.4
XRS 1	22.0	24.8	30.0	36.7	42.0	51.0
XRS 2	30.0	34.1	45.0	54.5	56.0	69.5
XRS 3	35.0	41.0	56.0	68.7	68.0	83.4
XRS 4	40.0	46.8	66.0	81.0	78.0	94.9
XRS 5	44.0	51.8	75.0	92.0	85.5	104.8
XRS 6	48.0	56.3	83.0	103.0	92.5	113.8
XRS 7	51.2	60.4	90.0	111.5	98.5	121.9
XRS 8	55.0	64.2	97.0	120.3	104.5	129.4
XRS 8.5	56.3	66.0	100.0	124.5	107.0	133.0

TABLE 3.2 8. Rounded minimum values of cover depths

Rounded mínimum cover depths						
b=1.50	XS1		XS2		XS3	
	50 years	100 years	50 years	100 years	50 years	100 years
XRD 0.5	20	25	20	25	35	40
XRS 1	25	30	30	40	45	55
XRS 2	30	35	45	55	60	70
XRS 3	35	40	55	70	70	N.R.*
XRS 4	40	50	65	N.R.*	N.R.*	N.R.*
XRS 5	45	55	75	N.R.*	N.R.*	N.R.*
XRS 6	50	60	N.R.*	N.R.*	N.R.*	N.R.*
XRS 7	55	65	N.R.*	N.R.*	N.R.*	N.R.*
XRS 8	60	N.R.*	N.R.*	N.R.*	N.R.*	N.R.*
XRS 8.5	65	N.R.*	N.R.*	N.R.*	N.R.*	N.R.*

*Not recommended

servative. If a further refinement would be required reported values for a could be divided by $\sum\alpha=1$ to normalize the values. However, for this application and in order to follow EN1990 procedure, no normalization to 1 was adopted.

Another conclusion from this sensitivity analysis is that the most sensitive parameter are the chloride ingress rate and the aging factor. Then corrosion rate in this case is not predominant as the values are very high resulting in relatively short propagation periods not impacting significantly in the total service life except as will be justified in next paragraphs.

3.2.4 Design values

3.2.4.1 Design values for propagation period

Since the additive definition of service life: initiation + propagation period and given the fact that concrete cover is only affecting the first one, in order to determine the required cover for each exposure class and concrete property will obtained by subtraction of propagation period from the total required service life.

$$t_{dep}\,(cover) = Service\ Life - t_{prop} \qquad \text{Eq. 3.2.8}$$

Applying design values to Eq. 3.2.8, yields:

$$t_{dep,d}\,(cover) = Service\ Life - t_{prop,d} \qquad \text{Eq. 3.2.9}$$

Therefore, design values for several reliability levels are obtained considering a log-normal distribution, 500 µm as maximum pitting attack giving:

$$t_{prop,d} = \frac{50}{V_{corr,d}} \qquad \text{Eq. 3.2.10}$$

Where $V_{corr,d}$ can be calculated as:

$$V_{Corr,d} = V_{Corr,\mu}\, e^{\,0.3\,\beta\,Cov} \qquad \text{Eq. 3.2.11}$$

Where α = –0.30 is adopted for XS cases. Calculated values for corrosion rate and propagation period until P_{corr} = 500 µm (pitting and end of service life) were given in Table 3.2.5. In view of the short design propagation periods, no propagation has been discounted from the initiation in the calculation of service life.

3.2.4.2. Cover depths for Chloride induced corrosion

The cover depth values are given in terms of $c_{min,dur}$ (where 10 mm for tolerance is subtracted from the design value of concrete cover). Table 3.2.7 shows the calculated minimum cover depth values (in mm) for 50 and 100 years for each ERC (from 0.5 to 7) and exposure classes XS1 to XS3). They should be rounded to the closest value ranked every 5 mm. The rounded values are shown in Table 3.2.8.

3.2.5 *References Chlorides*

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