ANNEX 9

Additional considerations on durability

1. Calculations relating to the Durability Limit State

The Durability Limit State is defined as the failure occurring due to the characteristic working life of the structure not being reached, as a result of the concrete or reinforcement deterioration processes reaching such a degree that they prevent the structure from behaving in accordance with the assumptions under which it was designed.

In order to check the Durability Limit State, this Code lays down a semi-probabilistic procedure similar to that adopted for the other Limit States.

When checking the Limit State, the following condition must be met:

$$t_L > t_d$$

where:

t_L Estimated value of the working life
t_d Design value of the working life

The design working life is defined as the characteristic working life multiplied by a safety factor:

$$t_d = y_t \ t_g$$

where:

t_d Design working life
γ_t Safety factor for working life with value $\gamma_t = 1{,}10$
t_g Design working life

1.1 General method

The general calculation method involves the following stages:

1. Choice of the design working life, according to 5.1.
2. Choice of the safety factor for working life
3. Identification of the environmental exposure classes to which the structure may be subject. For each class, identification of the predominant deterioration process.
4. Selection of the durability model corresponding to each deterioration process. Section 1.2 of this Annex contains some of the applicable models for the reinforcement corrosion processes.
5. Application of the model and estimation of the working life of the structure t_L.
6. Checking of the Limit State for each of the deterioration processes identified as relevant to the durability of the structure.

1.2. Durability models for the corrosion processes

1.2.1 General

In the case of corrosion, both by carbonation and by chlorides, the total time t_L needed for the attack or deterioration to become significant can be expressed as:

$$t_L = t_i + t_p$$

where:

- t_i Corrosion initiation period, understood as the time taken by the penetration front of the aggressive agent to reach the reinforcement thereby causing the corrosion to start.
- t_p Propagation period (propagation time of the corrosion until the structural element suffers significant deterioration).

This section sets out some of the applicable models for estimating the development of the deterioration processes linked to the corrosion of reinforcements. The Designer may opt for any other model endorsed by the specialised bibliography.

When checking the Limit State in the case of active reinforcements, the propagation period shall be regarded as $t_p=0$.

In the case of post-tensioned active reinforcements which are placed in accordance with the minimum covers laid down in the main articles, this Limit State does not usually need to be checked.

1.2.2 Initiation period

Both carbonation and chloride penetration are diffusion processes through the pores of the concrete and which may be modelled in accordance with the following expression:

$$d = K. \sqrt{t}$$

where:

- d Depth of penetration of the aggressive agent, for an age t.
- K Factor which depends on the type of aggressive process, the characteristics of the material and the environmental conditions.

1.2.2.1 Carbonation model

The period of time required for carbonation to occur at a distance d from the surface of the concrete may be estimated using the following expression:

$$t = (d/K_c)^2$$

where:

- d Depth, in mm.
- t Time, in years.

The carbonation factor K_c may be determined as:

$$K_c = c_{env} \cdot c_{air} \cdot a \cdot f_{cm}^{b}$$

where:

f_{cm} Mean compressive strength of the concrete, in N/mm², which may be estimated from the specified characteristic strength *(f_{ck}).*

$$f_{cm} = f_{ck} + 8$$

c_{env} Environmental factor, according to Table A.9.1.
c_{air} Air-entraining factor, according to Table A.9.2.
a, b Parameters which are a function of the type of binder, according to Table A.9.3.

Table A.9.1
Factor c_{env}

Environment	c_{env}
Protected from rain	1
Exposed to rain	0,5

Table A.9.2
Factor c_{air}

Occluded air (%)	c_{air}
< 4,5%	1
≥ 4,5%	0,7

Table A.9.3
Coefficients *a* and *b*

Binder	Cements from Guidelines RC 03	*a*	*b*
Portland cement	CEM I CEM II/A CEM II/B-S CEM II/B-L CEM II/B-LL CEM II/B-M CEM/V	1800	-1,7
Portland cement + 28% fly ash	CEM II/B-P CEM II/B-V CEM IV/A CEM IV/B	360	-1,2
Portland cement + 9% silica fume	CEM II/A-D	400	-1,2
Portland cement + 65% slag	CEM I II/A CEM III/B	360	-1,2

1.2.2.2 Chloride penetration model

The period of time required for a chloride concentration C_{th} to occur at a distance d from the surface of the concrete may be estimated using the following expression:

$$t = \left(\frac{d}{K_{Cl}} \right)^2$$

where

- d Depth, in mm.
- t Time, in years.

The chloride penetration coefficient K_{Cl} has the following expression:

$$K_{Cl} = \alpha \sqrt{12D(t)} \left(1 - \sqrt{\frac{C_{th} - C_b}{C_s - C_b}} \right)$$

where:

α Unit conversion factor equal to 56157.

D(t) Chloride effective diffusion coefficient, for age t, expressed in cm²/s.

C_{th} Critical chloride concentration, expressed in % of cement weight.

C_s Chloride concentration in the surface of the concrete, expressed in % of cement weight. As this chloride concentration is usually determined as % of concrete weight, its equivalent % of cement weight can be calculated using the cement content of the concrete (in kg/m^3) as:

C_s (% of cement weight) = C_s (% of concrete weight) * (2300/cement content)

C_b Content of chloride from materials (aggregates, cement, water, etc.), when the concrete mix is prepared.

The chloride diffusion coefficient varies with the age of the concrete according to the following expression:

$$D(t) = D(t_0) \left(\frac{t_0}{t} \right)^n$$

where $D(t_0)$ is the chloride diffusion coefficient at age t_0, $D(t)$ is the coefficient at age t, and n is the age factor which may be taken, in the absence of specific values determined through tests on the concrete in question, as equal to 0,5.

In order to use the chloride penetration model, the value of $D(t_0)$ determined through specific diffusion tests may be used (in which case t_0 would be the age of the concrete at which the test was performed) or the values in the following table may be used (determined for t_0 = 0,0767).

Table A.9.4

Coefficients D (t_0) (x10^{-12} m^2/s)

Type of cement	w/c = 0,40	w/c = 0,45	w/c = 0,50	w/c = 0,55	w/c = 0,60
CEM I	8,9	10,0	15,8	19,7	25,0
CEM II/A-V	5,6	6,9	9,0	10,9	14,9
CEM III	1,4	1,9	2,8	3,0	3,4

The critical chloride concentration (C_{th}) must be established by the Designer in accordance with the specific considerations for the structure. Under normal conditions, a value of 0,6% of the cement weight may be adopted for checking the Limit State in relation to the corrosion of the passive reinforcements. In the case of pre-tensioned active reinforcements, a limit value of C_{th} of 0,3% of the cement weight may be adopted.

The value of C_s depends on the external conditions, particularly the orography of the ground and the predominant winds in the area, in the case of environments close to the coast. C_s also varies with the age of the concrete, reaching its maximum value at 10 years. In the absence of values determined through tests on concrete structures situated in the vicinity, the Designer shall assess the possibility of adopting a value of C_s in accordance with Table 4.9.4, according to the general exposure class indicated in 8.2.2:

Table A.9.4

Chloride concentration at the surface of the concrete

General exposure class	IIIa		IIIb	IIIc	IV
Distance from the coast	Up to 500 m	500 m – 5000 m	Any		—
C_s (% of concrete weight)	0,14	0,07	0,72	0,50	0,50

1.2.3 Propagation period

The propagation stage is regarded as having ended when an unacceptable loss of section of the reinforcement occurs or when cracks appear in the concrete cover. The period of time taken for this to occur may be determined using the following expression:

$$t_p = \frac{80}{\phi}\frac{d}{v_{corr}}$$

where

- t_p Propagation time, in years.
- d Cover thickness, in mm.
- ϕ Diameter of the reinforcement, in mm.
- V_{corr} Corrosion rate, in μm/year.

In the absence of specific experimental data for the concrete and the specific environmental conditions of the structure, the corrosion rate may be determined from Table A.9.5.

Table A.9.5

Corrosion rate Vcorr according to the general exposure class

General exposure class			V_{corr} (μm/year)
Normal	High humidity	IIa	3
	Average humidity	IIb	2
Marine	Aerial	IIIa	20
	Submerged	IIIb	4
	In tidal zone	IIIc	50
With chlorides other than from the marine environment		IV	20

1.2.4 Estimation of working life due to the corrosion of reinforcements

Therefore, the total time, determined by adding together the initiation period and the corrosion propagation period, will be, in the case of corrosion by carbonation:

$$t_L = t_i + t_p = \left(\frac{d}{K_c}\right)^2 + \frac{80}{\phi}\frac{d}{v_{corr}}$$

In the case of corrosion by chlorides, this will be:

$$t_L = t_i + t_p = \left(\frac{d}{K}\right)^2 + \frac{80}{\phi}\frac{d}{v_{corr}}$$

2. Contribution of coating mortars to the cover of reinforcements

The articles in this Code allow the contribution of coatings which are impermeable, definitive and permanent compacts to be taken into account. In this respect, in the general exposure classes IIa, IIb and IIIa, without a specific exposure class, various alternatives may be used. If coating mortars are used, the value by which the thickness of mortar used must be multiplied to determine the equivalent cover which may be added to the actual concrete cover is defined as the “cover equivalence factor (λ)”. Tables A.9.6 and A.9.7 provide the values of λ for the most common environments in the case of building structures. Under no circumstances coating thicknesses in excess of 20 mm shall be used.

Table A.9.6
Cover equivalence factor for mortars
in environments IIa and IIb

Carbonation rate (mm/day1/2)	λ
≤ 2,0	0,5
≤ 1,0	1,0
≤ 0,7	1,5
≤ 0,5	2,0

Table A.9.7
Cover equivalence factor for mortars in environment IIIa

Chloride penetration rate (mm/day1/2) (*)	λ
≤ 3,4	0,5
≤ 1,7	1,0
≤ 1,1	1,5
≤ 0,9	2,0

(*) In order to determine the chloride penetration rate, and in the absence of a specific regulation, it is recommended that the test conditions described in Chapter 3 of standard AASTHO T259-80 are used. These conditions should be maintained until ages of not less than 90 days and the chloride penetration rate should be determined by any appropriate procedure (such as, for example, by colorimetric determination of the chloride penetration front with $AgNO_3$ at different intermediate ages).

Alternatively, for environment IIIa, the equivalence factor criterion laid down in Table A.9.8 may also be used.

Table A.9.8
Cover equivalence factor for mortars
in environment IIIa

Capillary action (kg/m^{2}h1/2) according to Recommendation RILEM CPC 11.2.	λ
≤ 0,40	0,5
≤ 0,20	1,0
≤ 0,15	1,5
≤ 0,10	2,0

So that a mortar can be used as indicated in this section, its components (cement, aggregates, additives, additions, etc.) must comply, where applicable, with the specifications for each of these in this Code. In addition, regardless of the value of its equivalence factor, the specifications in Table A.9.9 must also be met.

Table A.9.9
Characteristics of the mortar to be used in coatings,
in order to be taken into account for the purposes of this Annex.

Characteristic	Requirement
Flexural strength according to UNE-EN 1015-11	≥ 2 N/mm^2
Modulus of elasticity according to ASTM C 469	≤ 25000 N7mm^2
Drying shrinkage, at 28 days, according to ASTM C 157	≤ 0,04%
Bond strength according to UNE-EN 1542	≥ 0,8 N/mm^2
Thermal expansion coefficient according to UNE-EN 1770	≤ 11,7 x 10-6°C-1

If other coatings are used, or in environments other than the above, the Designer must prove, by means of documents, that the protection of the reinforcements in the precast element is similar to that which the thickness of concrete replaced would have provided. To this end, the manufacturer of coating products other than those above must guarantee, by means of documents, their performance and, among other aspects, at least the equivalence factor of the coating.

The specifications in the articles strictly correspond to floor slab durability requirements. Other criteria such as, for example, aesthetic or fire protection criteria may require greater cover thicknesses or the application of other specific protection.

In the case of highly aggressive environments, the value of the covers and the other design provisions must be established, after consulting the specialised technical literature, according to the nature of the environment, type of structural element concerned, etc.