6. CHLORIDE PENETRATION

6.1 General

In Fig. 6.1.1, the part (tab) of the logical flowchart of EUCON® is presented for the simulation of chloride penetration into concrete, and the estimation of the service life as regards corrosion induced by the chloride-initiation mechanism. The tab contains:

- a field that the user introduces the **input data** as regards the *environmental conditions* where the concrete structure is exposed.
- a field that the user is informed on the *main concrete characteristics, the* Cl^- *diffusivity*, and Cl^- *binding characteristics,* which all **influence** significantly the penetration.
- a field that the user introduces the *initial-boundary conditions and the threshold for corrosion*, and another field that the user introduces the *solution and output parameters*.
- a **calculation button**, for estimation of Cl^- profiles into concrete at various ages, as well as the corrosion-initiation period for a given cover to reinforcement *(on results subtab).*
- There is also the possibility to estimate the above results in the case of use of ***a protection measure***, such as waterproof sealants *(on protection subtab).*

CHLORIDE PENETRATION

INPUT

Tab "MIX DESIGN" data

Tab "PHYSICOCHEMICAL CHARACTERISTICS" data

Environmental conditions (exposure class, Cl^- concentration, exposure degree, etc.)

Initial-boundary conditions. Threshold for corrosion. Solution and output parameters.

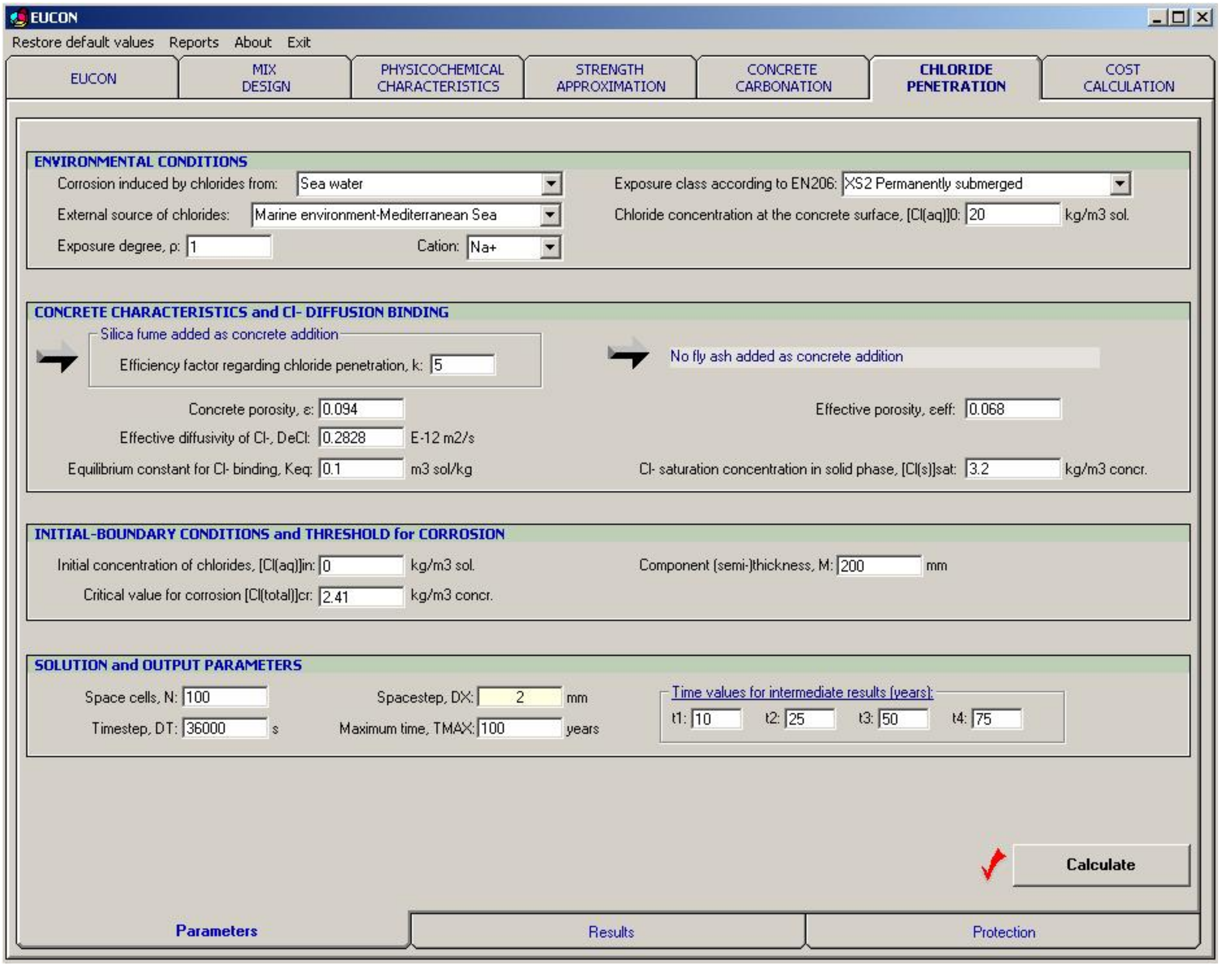
▼

CALCULATION

(For specific concrete cover and protection: corrosion-initiation period)

Figure 6.1.1 Logical diagram for computer simulation of chloride penetration in concrete.

A general view of this tab is given as Fig. 6.1.2. The user has to fill in the “white boxes” within the permitted limits or to accept the default values, and then to press the calculation button in order to have an estimation of Cl$^-$ profiles into concrete at various ages, as well as the corrosion-initiation period. For the mathematical formulae used for these calculations and further questions, **please always advise the *Theoretical Background* [1], chapter 6**. In the sequence, each part of this tab is discussed in detail.



ENVIRONMENTAL CONDITIONS

Corrosion induced by chlorides from: Sea water
External source of chlorides: Marine environment-Mediterranean Sea
Exposure degree, p: 1
Cation: Na+
Exposure class according to EN206: XS2 Permanently submerged
Chloride concentration at the concrete surface, [Cl(aq)]0: 20 kg/m3 sol.

CONCRETE CHARACTERISTICS and Cl- DIFFUSION BINDING

Silica fume added as concrete addition
Efficiency factor regarding chloride penetration, k: 5
No fly ash added as concrete addition
Concrete porosity, ε: 0.094
Effective porosity, εeff: 0.068
Effective diffusivity of Cl-, DeCl: 0.2828 E-12 m2/s
Equilibrium constant for Cl- binding, Keq: 0.1 m3 sol/kg
Cl- saturation concentration in solid phase, [Cl(s)]sat: 3.2 kg/m3 concr.

INITIAL-BOUNDARY CONDITIONS and THRESHOLD for CORROSION

Initial concentration of chlorides, [Cl(aq)]in: 0 kg/m3 sol.
Critical value for corrosion [Cl(total)]cr: 2.41 kg/m3 concr.
Component (semi-)thickness, M: 200 mm

SOLUTION and OUTPUT PARAMETERS

Space cells, N: 100
Timestep, DT: 36000 s
Spacestep, DX: 2 mm
Maximum time, TMAX: 100 years
Time values for intermediate results (years):
t1: 10
t2: 25
t3: 50
t4: 75

Figure 6.1.2 General view of the tab “CHLORIDE PENETRATION” of the EUCON® program.

6.2 Environmental conditions

Corrosion induced by chlorides from:	Use the button "▼" and select among: *sea water* or *other than from sea water*. DEFAULT VALUE: Sea water
Exposure class according to EN 206:	According to EN 206, *environmental actions* are those chemical and physical actions to which the concrete is exposed and which result in effects on the concrete or reinforcement or embedded metal that are not considered as loads in structural design. The environmental actions are classified as ***exposure classes,*** and for the case of corrosion of reinforcement induced by chlorides, these classes are presented in Table 6.2.1. The exposure classes to be introduced (by using the button "▼") depend on the provisions valid in the place of use of the concrete. LIMITS: as given in Table 6.2.1 DEFAULT VALUE: XS2 Permanently submerged
External source of chlorides:	Use the button "▼" and select the specific external source of chlorides. LIMITS: If the Cl^- originate from sea water choose between *various marine environments* (Atlantic Ocean, Mediterranean Sea, North Sea, Baltic Sea, Experimental/Other). If the Cl^- originate from other than sea water choose between *various external environments* (De-icing salts, Swimming pools, Industrial waters, Other). This selection has a significant effect on chloride concentration at the concrete surface (see below), and furthermore on the level of Cl^- values in concrete. DEFAULT VALUE: Marine environment- Atlantic Ocean
Chloride concentration at the concrete surface, [Cl(aq)]0:	According to the above characteristics, typical Cl^- concentrations at the concrete surface are appeared. Accept them or introduce a new value. UNITS: kg/m^3 aqueous solution LIMITS: They depend on the type of the external source of chlorides: Atlantic Ocean: 20 ± 3, Mediterranean Sea: 20 ± 3, North Sea: 16 ± 3, Baltic Sea: 4 ± 1, Experimental/Other: >0 (default: 100). De-icing salts: >0 (def.: 100), Swimming pools: >0 (def.: 20), Industrial waters: >0 (def.: 20), Other: >0 (def.: 20).
Exposure	Introduce the ratio of the exposure time to chlorides to the total time of

degree, ρ:	a complete exposure/non-exposure cycle. The final chloride concentration for estimations will be: [Cl(aq)]0 = ρ [Cl(aq)]0. UNITS: dimensionless LIMITS: $0 < \rho \leq 1$. DEFAULT VALUE: For all exposure types is equal to 1, except for de-icing salts that equals to 0.2.
Cation:	Use the button "▼" and select among: Na^+ or Ca^{2+}. It is the cation that accompanies the anion Cl^- and influences its diffusivity. DEFAULT VALUE: Na^+. For marine environments only Na^+.

Table 6.2.1 Exposure classes according to EN 206 for possible corrosion induced by chloride and correlation with measurable relative humidity (RH).

Class	Description of the environment	Informative examples	RH (%)
Corrosion induced by chlorides from sea water			
Where concrete containing reinforcement or other embedded metal is subjected to contact with chlorides from sea water or air carrying salt originating from sea water, the exposure shall be classified as follows:			
XS1	Exposed to airborne salt but not in direct contact with sea water	Structures near to or on the coast	< 80
XS2	Permanently submerged	Parts of marine structure	> 98
XS3	Tidal, splash and spray zones	Parts of marine structure	> 80
Corrosion induced by chlorides other than from sea water			
Where concrete containing reinforcement or other embedded metal is subjected to contact with water containing chlorides including de-icing salts, from sources other than from sea water, the exposure shall be classified as:			
XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides	< 80
XD2	Wet, rarely dry	Swimming pools, concrete exposed to industrial waters containing chlorides	> 98
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides, pavements, car park slabs	> 80

6.3 Concrete characteristics and Cl$^-$ diffusion-binding

Efficiency factor regarding chloride penetration, k:	The efficiency factor (or k-value) is defined as the part of the silica fume, fly ash or other SCM that can be considered as equivalent to portland cement (CEM I), providing the same concrete properties. Introduce here the efficiency factors or use the default values, if you do not have more accurate experimental results. UNITS: dimensionless LIMITS: $0 \leq k \leq 7$ DEFAULT VALUE: These in Table 6.3.1
Concrete porosity, ε:	It is a reminder of the ratio of final pore volume to the total volume of the concrete (complete cement hydration and pozzolanic action, see tab “PHYSICOCHEMICAL CHARACTERISTICS”).
Effective porosity, εeff:	The effective porosity of concrete regarding chloride diffusion. It is calculated from Eq. (6.2.6) of the reference [1]. UNITS: dimensionless LIMITS: 0 < εeff < 1
Effective diffusivity of Cl$^-$, DeCl:	The effective diffusivity of Cl$^-$ in concrete, calculated from Eq. (6.2.5), ref. [1]. For XS2, XS3, XD2 and XD3, we suppose an almost saturated concrete. For XS1 and XD1, we suppose a partly-saturated concrete, with diffusivity of an order of magnitude less than that of the saturated concrete (for safe estimations we multiply by 0.2 instead of 0.1). UNITS: 10^{-12} m^2/s LIMITS: 0 < DeCl
Equilibrium constant for Cl$^-$ binding, Keq:	The equilibrium constant for Cl$^-$ binding in solid phase of concrete. UNITS: m^3 sol /kg LIMITS: 0 < Keq < 10 DEFAULT VALUE: 0.1 m^3 sol /kg
Cl$^-$ saturation concentration in solid phase, [Cl(s)]sat:	The saturation concentration of Cl$^-$ in the solid phase. It is calculated from Eq. (6.2.8) of the reference [1]. UNITS: kg/m^3 concrete LIMITS: 0 < [Cl(s)]sat < 100

Table 6.3.1 Efficiency factors (k-values) regarding chloride penetration for various supplementary cementing materials [1].

	Cementitious/ pozzolanic materials	Chloride resistance
1	Portland clinker	1
2	Blast furnace slag	2.2
3	Silica fume	5
4	Pozzolana (natural)	1
5	Metakaolin	5
6	Siliceous fly ash	3
7	Calcareous fly ash	2.2
8	Burnt shale	2.2
9	Limestone	0.1
10	Various SCM for CEM II	2.2
11	Various SCM for CEM IV	2.2
12	Various SCM for CEM V	2.2

6.4 Initial-boundary conditions and threshold for corrosion

Initial concentration of chlorides, [Cl(aq)]in:	Introduce the initial (at t=0) concentration of Cl^- in the aqueous phase of the fresh concrete. Add the possible quantities of Cl^- from all concrete constituents and convert them per m^3 of the effective water. For example: 0.2% bw Cl^- in cement, with C=300 kg/m^3 concr. gives 0.6 kg Cl^-/m^3 concr., and if W=150 kg/m^3 concr., then [Cl(aq)]in=4 kg/m^3 sol. UNITS: kg/m^3 aqueous solution DEFAULT VALUE: 0 kg/m^3 sol.
Component (semi-) thickness, M:	Introduce the distance between the outer surface and the axis of symmetry of the concrete component, if both opposite sides are exposed to the same environment. If only one side is exposed and the opposite is protected, then introduce the whole thickness of the component. UNITS: mm

	LIMITS: $50 \leq M$ DEFAULT VALUE: 200 mm.
Critical value for corrosion, [Cl(total)]cr:	The critical total concentration of Cl^- for steel corrosion. It is calculated from Eq. (6.2.12) of the reference [1]. UNITS: kg/m^3 concrete LIMITS: > 0.004 $\{K+CS + \sum(P_{ACT})\}$ kg total chlorides/ m^3 concrete

6.5 Solution and output parameters

Space cells, N:	The Eq. (6.2.1) of ref. [1] is solved numerically by using the *finite difference method.* According to this numerical method, the distance M is separated at N discrete cells where the difference-equation applies. UNITS: dimensionless LIMITS: $50 < N$ DEFAULT VALUE: 100
Spacestep, DX:	The space derivative as a finite difference. It is calculated as M/N. UNITS: mm
Timestep, DT:	The time derivative as a finite difference. UNITS: seconds (s) LIMITS: $60 \leq DT < 72{,}000$ DEFAULT VALUE: 36000 s for TMAX=100 years
Maximum time, TMAX:	The maximum time up to the user is interested to predict the Cl^- profile. UNITS: years LIMITS: $0 < TMAX \leq 1{,}000$ DEFAULT VALUE: 100 years
Time values for intermediate results, t1, t2, t3, t4:	The intermediate times when the user wishes to know the Cl^- profiles in the concrete. UNITS: years LIMITS: $0 < t1 < t2 < t3 < t4 < TMAX$ DEFAULT VALUE: t1=10 years, t2=25 years, t3=50 years, t4=75 years

6.6 Calculation and results

For the mathematical model used for these calculations and for further questions, **please advise the *Theoretical Background* [1], chapter 6**. Click on the "**Calculate**" button to estimate the total Cl$^-$ profiles in concrete at various ages, as well as the critical time for chloride-induced corrosion, as a function of concrete cover. Click on the "**Cancel**" button if you wish to terminate the calculations, loosing however all intermediate results. The calculation is completed when all space in the next indication bar is filled. When the calculation is on progress, do not change any input parameters because the output will be wrong.

When the calculation is completed (all the indication bar has been filled and disappeared) click on the "**Results**" subtab where all results are summarized as follows:

Total chloride concentration profiles at various ages:	In the figure is given the total chloride concentration as a function of the distance from the outer surface of concrete at various ages. The corrosion threshold is also indicated by a red line that cross the Cl-profiles. From the intersection is calculated the following table that gives the time needed for Cl-concentration to exceed the critical value for corrosion at the given distance from the surface. UNITS: Concentration in kg/m^3 concrete, versus distance in mm, and for various ages in years.
Concrete service life as a function of concrete cover to reinforcement:	In the table is given the estimation of the time (critical time for chloride-induced corrosion, **tcr,chlor**) required for the total chloride concentration surrounding the reinforcement (located at a distance **c** from surface- cover) to increase over the threshold for depassivation, [Cl$^-$(total)]cr. We can state that the service lifetime of a structure, regarding chloride penetration, is at least tcr,chlor. These results are given also in the adjacent figure that helps to calculate intermediate estimations between the points. UNITS: Concrete service life in years, versus cover in mm.

By obtaining the above estimation for the ***concrete service life*** as regards a chloride-induced corrosion of reinforcement, you may:

- **accept these results** and continue in the next tab to estimate cost.
- Otherwise, **you may change any input data mainly from the tab "MIX DESIGN"** in order to correct the output results of this tab, **until final acceptance.**
- In addition, **you may consider a protection measure,** as those given below, in order to prolong the service life.

6.7 Protection

The most effective protection measure against corrosion is the serious consideration of all corrosion parameters ***at the design stage***. Protection of the reinforcement from chloride-initiated corrosion can be achieved by selecting the *concrete cover and the mix design* so that critical Cl-concentration will not reach the bar surface within the expected lifetime of the structure. In the circumstances when protection against corrosion cannot guaranteed by selection of the materials and proportions of the concrete, depth of cover and attention to sound construction practice, one or more of the following **extra protective measures** may then be taken [1]. Select from the following the extra protective measure that you wish and follow the directions for application to estimate the new service life:

- **Addition of a *corrosion inhibiting admixture***, such as calcium nitrite, to a fresh concrete, or by impregnation to a hardened concrete.

  Directions: Please, seek advice the admixture-manufacturer company or the inhibitor dealer on how this inhibitor increases the corrosion threshold (or improves other properties), go back to the *Parameters section* of this tab, enhance the corrosion threshold (or other property) and run again the model to obtain the new estimation.

- **Use of *corrosion-resistant stainless steel* reinforcing bars, or *epoxy-coated* conventional bars.**

  Directions: This measure does not affect the calculated Cl-profiles into concrete. Please, seek advice the bar-manufacturer company or the bar dealer on how long this resistance against corrosion lasts, go back to the *Results section* of this tab, and refer to figures in order to see the evolution of the corrosion process after resistance elimination.

- ***Cathodic protection of the reinforcement***, i.e., applying a voltage from an external source sufficient to ensure that all of the steel remains permanently cathodic.

  Directions: This measure does not affect the calculated Cl-profiles into concrete. Please, seek advice the provider company on how long this protection lasts, go back to the *Results section* of this tab, and refer to figures in order to see the evolution of the corrosion process after protection elimination.

- **Applying an *impregnation technique to the concrete***, to reduce chloride and moisture ingress.

  Directions: Please, seek advice the manufacturer company or the material/technique dealer on how it reduces porosity and Cl-diffusivity properties, go back to the *Parameters section* of this tab, enhance accordingly these properties and run again the model to obtain the new estimation.

- **Applying a *protective coating to the concrete***, to eliminate chloride and moisture ingress for some period.

  Directions: If a waterproof sealant would be used, please, seek advice the manufacturer company or the material dealer on how long this protection lasts, say X: 5 years.

  Let us suppose, that the concrete surface remains non-protected for the following period, say Y: 5 years.

  Then, a repair takes place which will protect the concrete for X years, and the cycle again starts. The exposure degree, ρ, is calculated as $\rho = Y / (X + Y)$:_______. Go back to the *Parameters section* of this tab, introduce this exposure degree, ρ, and run again the model to obtain the new estimation.