5. CONCRETE CARBONATION

5.1 General

In Fig. 5.1.1, the part (tab) of the logical flowchart of EUCON® is presented for the calculation of the concrete carbonation depth and the estimation of the service life as regards corrosion induced by the carbonation-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 and CO_2 diffusivity* that influence concrete carbonation.
- a **calculation button**, for estimation of concrete service life for a given cover to reinforcement.
- a **calculation button**, for estimation of carbonation depth at a given concrete age.
- There is also the possibility to estimate the above results in the case of use of *a protection measure*, such as waterproof sealants or cement – lime mortar coatings.

CONCRETE CARBONATION

INPUT

Tab "MIX DESIGN" data

Tab "PHYSICOCHEMICAL CHARACTERISTICS" data

Environmental conditions (exposure class, relative humidity, CO_2-content in air)

▼

CALCULATION

(For specific concrete cover and protection: corrosion-initiation period, corrosion-propagation period, total service life)

Figure 5.1.1 Logical diagram for computer simulation of the concrete carbonation.

A general view of this tab is given as Fig. 5.1.2. 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 buttons in order to have an estimation for the concrete service life or the carbonation depth. For the algebraic formulae used for these calculations and further questions, **please always advise the *Theoretical Background* [1], chapter 5**. In the sequence, each part of this tab is discussed in detail.

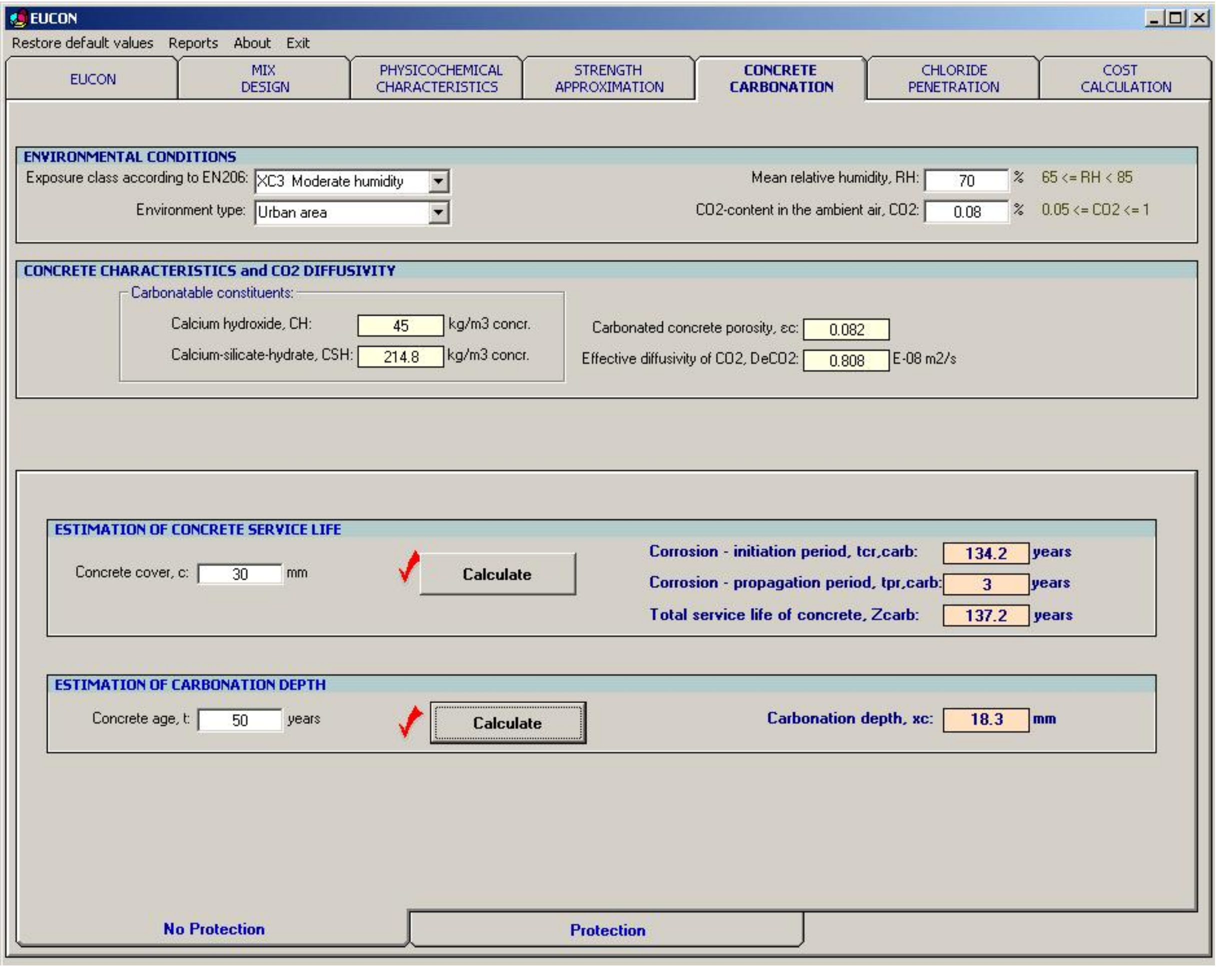

Figure 5.1.2 General view of the tab "CONCRETE CARBONATION" of the EUCON® program.

5.2 Environmental conditions

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 carbonation, these classes are presented in Table 5.2.1. 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 5.2.1 DEFAULT VALUE: XC3 Moderate humidity
Mean relative humidity, RH:	Introduce the relative humidity of the ambient air. UNITS: % LIMITS: They depend on exposure class and given in Table 5.2.1 DEFAULT VALUE: It is given in Table 5.2.1 for each class.
Environment type:	Use the button "▼" and select the environment type. LIMITS: choose between *urban area* (cities, traffic roads, industrial areas, places of human or animal concourse, etc.), *countryside* (villages, open country side areas, low traffic roads, etc.) or *experimental/other* (specific cases or experimental conditions). This selection has a significant effect on concrete carbonation. DEFAULT VALUE: urban area
CO2-content in the ambient air, CO2:	Introduce the carbon dioxide content in the ambient air at the concrete surface. UNITS: % LIMITS: They depend on environment type and have as follows: Urban area: $0.05 < CO2 \leq 1\%$ (0.08%) Countryside: $0.025 \leq CO2 \leq 0.05\%$ (0.035%) Experimental: $0 < CO2 \leq 100\%$ (3%) DEFAULT VALUE: It is given in the parentheses above.

Table 5.2.1 Exposure classes according to EN 206 for possible corrosion induced by carbonation and correlation with measurable mean relative humidity RH.

Class	Description of the environment	Informative examples	RH (%)	Mean RH (%)
1 No risk of corrosion or attack				
X0	For concrete with reinforcement or embedded metal: Very dry	Concrete inside buildings with very low air humidity	0≤RH<45	35
2 Corrosion induced by carbonation				
Where concrete containing reinforcement or other embedded metal is exposed to air and moisture, the exposure shall be classified as follows:				
XC1	Dry	Concrete inside buildings with low air humidity	45≤RH<65	55
	Permanent wet	Concrete permanently submerged in water	98≤RH≤100	98
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact, many foundations	90≤RH<98	90
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity, external concrete sheltered from rain	65≤RH<85	70
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2	75≤RH<90	80

5.3 Concrete characteristics and CO_2 diffusivity

Carbonatable constituents

Calcium hydroxide content, CH:	It is a reminder of the final calcium hydroxide content in the concrete volume (complete cement hydration and pozzolanic action, see tab “PHYSICOCHEMICAL CHARACTERISTICS”).
Calcium-silicate-hydrate content, CSH:	It is a reminder of the final calcium silicate hydrate content in the concrete volume (complete cement hydration and pozzolanic action, see tab “PHYSICOCHEMICAL CHARACTERISTICS”).

Carbonated-concrete porosity, εc:	It is a reminder of the ratio of final pore volume to the total volume of the carbonated concrete (complete cement hydration and pozzolanic action, see tab "PHYSICOCHEMICAL CHARACTERISTICS").
Effective diffusivity of CO2, DeCO2:	The effective diffusivity of CO_2 in carbonated concrete. It is calculated from Eq. (5.2.2) of the reference [1]. UNITS: 10^{-8} m^2/s LIMITS: 0 < DeCO2

5.4 Calculations

For the algebraic formulae used for these calculations and the theory that they based on, and for further questions, **please advise the *Theoretical Background* [1], chapter 5**. Click on the "**Calculate**" buttons to estimate:

Estimation of concrete service life

Concrete cover, c:	Introduce the concrete cover, i.e., the distance of reinforcement from the outer surface of concrete. In this case, we suppose a non-covered, non-protected concrete surface. UNITS: mm LIMITS: 0 ≤ c DEFAULT VALUE: 30 mm
Corrosion-initiation period, tcr,carb:	The critical time required for reinforcement depassivation due to carbonation. The estimation is based on Eqs. (5.2.3) and (5.2.6) of [1]. UNITS: years
Corrosion-propagation period, tpr,carb:	The critical time required for carbonation-induced corrosion to split the cover. The estimation is based on Eq. (5.3.7) of [1]. UNITS: years
Total service life of concrete, Zcarb:	The total calculated service life of a concrete structure regarding carbonation-induced depassivation mechanism. The estimation is based on Eq. (5.3.8) of [1]. UNITS: years

Estimation of carbonation depth

Concrete age, t:	Introduce the age of the concrete since mixing and exposing on the above particular environment. In this case, we suppose a non-covered, non-protected concrete surface. UNITS: years LIMITS: $0 \leq t$ DEFAULT VALUE: 50 years
Carbonation depth, xc:	The concrete carbonation depth measured from concrete surface. The estimation is based on Eqs. (5.2.1) and (5.2.5) of [1]. UNITS: mm

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

- **accept these results** and continue in the next tabs 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.

5.5 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 carbonation-initiated corrosion can be achieved by selecting the *concrete cover and the mix design* so that carbonation will not reach the bar surface within the expected lifetime of the structure.

If however, corrosion is predicted to be unavoidable during the designed service life, several additional protection measures can be applied. A way to avoid corrosion is *to isolate concrete and/or reinforcement from the environment* that contains CO_2 and/or moisture. This would be done by applying one or more *protective coatings* to a suitably prepared surface. The case of coating application on concrete surface will be further analysed.

The application of surface coatings to concrete as a means of reducing the rates of carbonation and corrosion is discussed and modelled in reference [1]. Actually, because a strong gas-tightness is almost impossible to achieve at a reasonable cost, these materials decrease simply the diffusion process of CO_2, O_2, and water vapour. The higher their thickness and the lower their permeability, the lower the diffusion rate of detrimental agents. These concepts have been taken into account for modelling, using the more general case presented in the sequence, where in addition the coating may be act as a material arresting carbonation.

Thus, two general cases are taken into consideration: **waterproof sealants** and **cement – lime mortar coatings:** *The user has to choose among these two types of additional protection (if required) to adopt or correct their characteristics and to calculate the life prolongation that they offer.*

● Waterproof sealants

These materials do not arrest carbonation, i.e., the calcium hydroxide content in the coating is zero (CH1=0) and the calcium-silicate-content in the coating is also zero (CSH1=0). The coating porosity is very low in order to reduce the CO_2 diffusivity, and depending on the coating thickness, an adequate prolongation of the service life may be achieved, provided the regular coating repairing and rehabilitation. It is also considered that the coating contains no significant microscopic cracks. Their porosity and effective diffusivity have to be provided by the manufacturer or to be measured. However, some default values may be used.

● Cement – lime mortar coatings

These materials do arrest carbonation, due to the existence of carbonatable constituents (CH, CSH) in their mass. A significant prolongation of the service life may be achieved, provided the regular coating repairing and rehabilitation. Their characteristics (carbonatable constituents' content and porosity can be estimated by using the same approach as this applied for concrete, see chapter 3 of [1]. The user has to click on the below box: **"Design of the Mortar Mix"** and to open a "Mortar mix design" window, with the following characteristics:

MORTAR MIX DESIGN

Cement for mortar coating

Cement type:	Use the button "▼" and select among the available cement types that may use in the mortar composition. LIMITS: You have to select among the available typical cement types: CEM I, CEM II/A-M, CEM II/B-M and CEM IV/B (according to EN 197). If the construction is an old one and a past cement type might be used, or another standard is applied, or more than one cement used, then you have to select the closest cement type from the above. DEFAULT VALUE: CEM II/B-M
Cement density, DC1:	Introduce the particle density of the cement. UNITS: kg/m^3 LIMITS: 2000 – 4000 kg/m^3 DEFAULT VALUE: 3100 kg/m^3
Cement content, C1:	Introduce the total cement content in the mortar volume. UNITS: kg cement / m^3 of mortar LIMITS: $0 \leq C1 < DC1$ DEFAULT VALUE: 270 kg/m^3

Lime for mortar coating

Lime type:	Use the button "▼" and select among the available lime types. We define as lime the dry $Ca(OH)_2$ without excess of water (in a water-saturated, surface-dry form). LIMITS: You have to select among the lime types: CL 90, CL 80, and CL 70 (according to EN 459-1 [4]), assuming a purity in lime of 90%, 80%, and 70%, respectively (PL = 0.9, 0.8, 0.7). DEFAULT VALUE: CL 90 (purity 90% in $Ca(OH)_2$)
Lime density, DL1:	Introduce the particle density of the lime. UNITS: kg/m^3 LIMITS: 1500 – 3500 kg/m^3 DEFAULT VALUE: 2350 kg/m^3
Lime content,	Introduce the total lime content in the mortar volume.

L1:	UNITS: kg lime / m^3 of mortar LIMITS: 0≤L1<DL1 DEFAULT VALUE: 135 kg/m^3

Active additions for mortar coating

Fly ash type:	Use the button "▼" and select the fly ash type you may use in mortar. LIMITS: choose between siliceous and calcareous fly ash. DEFAULT VALUE: siliceous fly ash
Fly ash density, DF1:	Introduce the particle density of fly ash. UNITS: kg/m^3 LIMITS: 1500 - 4000 DEFAULT VALUE: 2250 kg/m^3 for siliceous fly ash and 2660 kg/m^3 for calcareous fly ash
Fly ash content, F1:	Introduce the fly ash content in the mortar volume. UNITS: kg fly ash / m^3 of mortar LIMITS: 0≤F1<DF1 DEFAULT VALUE: 0 kg/m^3
Silica fume density, DS1:	Introduce the particle density of silica fume. UNITS: kg/m^3 LIMITS: 1500 - 4000 DEFAULT VALUE: 2260 kg/m^3
Silica fume content, S1:	Introduce the silica fume content in the mortar volume. UNITS: kg silica fume / m^3 of mortar LIMITS: 0≤S1<DS1 DEFAULT VALUE: 0 kg/m^3

Air in mortar coating

Air content, EAIR1:	The total entrained and entrapped air content in mortar. UNITS: % volume air /volume mortar LIMITS: 1-15%. DEFAULT VALUE: 6%

Water for mortar coating

Water density, DW1:	Introduce the water density. UNITS: kg/m^3 LIMITS: 900 - 1200 DEFAULT VALUE: 1000 kg/m^3
Water content, W1:	Introduce the total water content in the mortar volume. UNITS: kg water / m^3 of mortar LIMITS: $0 \leq W1 < DW1$ DEFAULT VALUE: 216 kg/m^3

click on the "Calculate" button to estimate:

Aggregates and Inert additions for mortar coating

Aggregate density, DA1:	Introduce the particle density of aggregates. UNITS: kg/m^3 LIMITS: 1000 - 4000 DEFAULT VALUE: 2600 kg/m^3
Aggregate content, A1:	The total aggregate content in the mortar volume. It is calculated from Eq. (5.4.8) of [1]. We suppose that the aggregates are internal saturated by water and their surface is dry. UNITS: kg aggregate / m^3 of mortar

Characteristic ratios in mortar

Water/cement ratio, W1/C1:	The ratio of the effective water content to cement content by mass in the fresh mortar. UNITS: dimensionless
Aggregate/cement ratio, A1/C1:	The ratio of the aggregate content to cement content by mass in the fresh mortar. UNITS: dimensionless
Lime/cement ratio, L1/C1:	The ratio of the lime content to cement content by mass in the fresh mortar. UNITS: dimensionless

Chemical and volumetric composition of mortar

Calcium hydroxide content, CH1:	The final calcium hydroxide content in the mortar volume (100% cement hydration and pozzolanic action)*. UNITS: kg / m^3 of mortar
Calcium-silicate-hydrate content, CSH1:	The final calcium-silicate-hydrate content in the mortar volume (100% cement hydration and pozzolanic action)*. UNITS: kg / m^3 of mortar
Carbonated-concrete porosity, εc1:	The ratio of pore volume (final) to the total volume of the carbonated mortar (100% cement hydration, pozzolanic action and carbonation)*. UNITS: dimensionless (by volume)

In order to introduce the above characteristics into the following "Coating characteristics", **the user has to click on the button "v"** at the lower-right corner of this window.

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*The CH1, CSH1 and εc1 are calculated as follows (based on chapter 2 of [1] and typical oxide compositions):

Cement type	*Clinker content, PK1 (%)*	*Suppl. cem. materials content, PSCM1 (%)*
CEM I	95	0
CEM II/A-M	80	15
CEM II/B-M	65	30
CEM IV/B	50	45

Clinker content in mortar: K1 =0.95(PK1/100)C1 and SCM content (from cement): P1 =0.95(PSCM1/100)C1

If : {1.617 S1 + 1.115 (or 0.483 if calcareous) F1 + 0.684 P1} $\leq$ {L1 PL + 0.256 K1}then the active contents: SACT1=S1, FACT1=F1, PACT1=P1

If : {1.617 S1 + 1.115 (or 0.483 if calcareous) F1 + 0.684 P1} > {L1 PL + 0.256 K1}then
CH1=0 and SACT1=R1 S1, FACT1=R1 F1, PACT1=R1 P1
where R1= {L1 PL + 0.256 K1} / {1.617 S1 + 1.115 (or 0.483 if calcareous) F1 + 0.684 P1}

CH1 = {L1 PL + 0.256 K1} – {1.617 SACT1 + 1.115 (or 0.483 if calcareous) FACT1 + 0.684 PACT1}
CSH1 = 2.85 {0.23 K1 + 0.874 SACT1 + 0.435 (or 0.277 if calcareous) FACT1 + 0.325 PACT1}
ε1 = {EAIR1/100 + W1/DW1} – {0.261 K1/1000 + 0.204 (or 0.195 if calcareous) FACT1/1000 + 0.154 PACT1/1000}
εc1 = ε1 – {0.05196 10^{-3} CH1 + 0.04495 10^{-3} CSH1}

Coating characteristics

Calcium hydroxide, CH1:	It is the final calcium hydroxide content in the coating/mortar volume (complete cement hydration and pozzolanic action). UNITS: kg/m^3 coating/mortar DEFAULT VALUES: for waterproof sealants: 0 for cement-lime mortar coatings: as calculated from the mortar design
Calcium-silicate-hydrate, CSH1:	It is the final calcium-silicate-hydrate content in the coating/mortar volume (complete cement hydration and pozzolanic action). UNITS: kg/m^3 coating/mortar DEFAULT VALUES: for waterproof sealants: 0 for cement-lime mortar coatings: as calculated from the mortar design
Coating porosity, εc1:	It is the ratio of final pore volume to the total volume of the carbonated coating/mortar. UNITS: dimensionless DEFAULT VALUES: for waterproof sealants: 0.1 for cement-lime mortar coatings: as calculated from the mortar design
Effective diffusivity of CO2, DeCO2.1:	The effective diffusivity of CO_2 in the carbonated coating/mortar. It is calculated from data of the reference [5]. UNITS: 10^{-8} m^2/s DEFAULT VALUES: for waterproof sealants: $164\ (\varepsilon c1)^{1.8}\ (1\text{-}RH/100)^{2.2}$ for cement-lime mortar coatings: $164\ [\ (\varepsilon c1) / (1\text{-}A1/DA1)\ ]^{1.8}\ (1\text{-}RH/100)^{2.2}$
Coating thickness, d:	Introduce the thickness of the mortar coating. UNITS: mm LIMITS: $0 \leq d$ DEFAULT VALUES: for waterproof sealants: 1 mm for cement-lime mortar coatings: 20 mm
Time of	Introduce the time of application of mortar coating after concrete

application of mortar coating, ta:	casting. Introduce a value if it is significant higher than 1 year. UNITS: years LIMITS: $0 \leq ta$ DEFAULT VALUE: 0 years

Estimation of corrosion initiation period

Concrete cover, c:	Introduce the concrete cover, i.e., the distance of reinforcement from the outer surface of concrete. UNITS: mm LIMITS: $xca \leq c$ DEFAULT VALUE: 30 mm
Time required for coating carbonation, td:	The time required for total carbonation of mortar coating. The estimation is based on Eqs. (5.4.1) of [1]. UNITS: years
Corrosion-initiation period, tcr,carb:	The critical time required for reinforcement depassivation due to carbonation. The estimation is based on Eqs. (5.4.6) of [1]. UNITS: years

Estimation of carbonation depth

Concrete age, t:	Introduce the age of the concrete since mixing and exposing on the above particular environment. UNITS: years LIMITS: $(ta+td) \leq t$ DEFAULT VALUE: 100 years
Initial carbonation depth of concrete, xca:	The initial (without any coating) carbonation depth of concrete. The estimation is based from Eq. (5.2.1) of [1] for t = ta and for parameter values equal to those of the concrete. UNITS: mm
Carbonation depth, xc:	The concrete carbonation depth measured from concrete surface. The estimation is based on Eqs. (5.4.5) of [1]. UNITS: mm

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

- **accept these results** and continue in the next tabs to estimate cost.
- Otherwise, **you may change any input data mainly from the tab "MIX DESIGN"or to improve the protection measure** in order to correct the output results of this tab, **until final acceptance.**