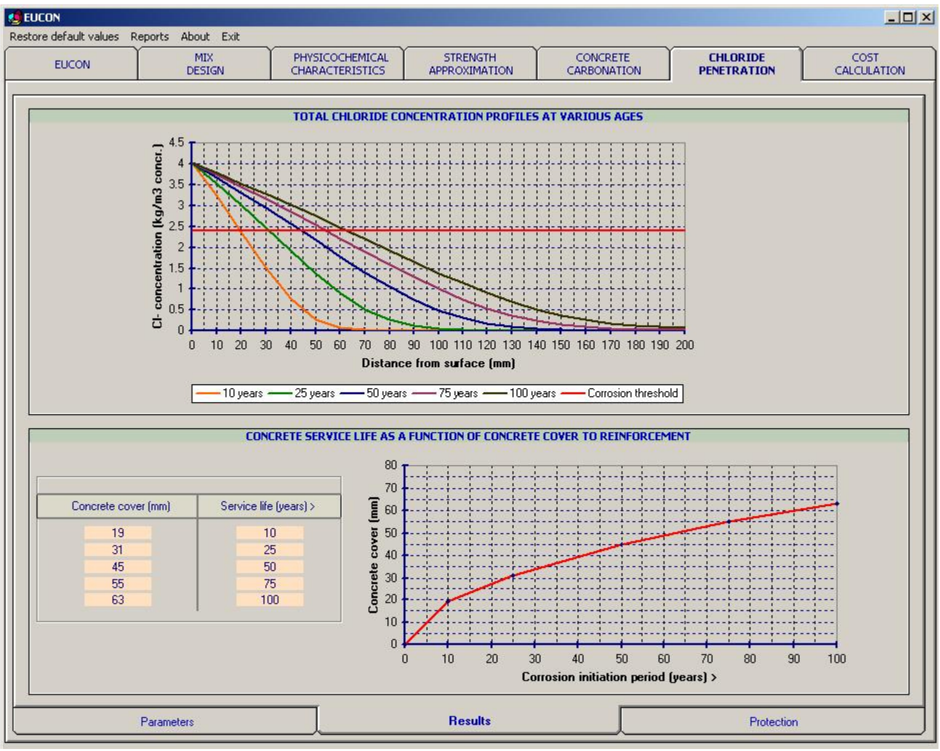
EUCON:

A SOFTWARE PACKAGE FOR ESTIMATION OF CONCRETE SERVICE LIFE

The User Manual



Concrete cover (mm)	Service life (years) >
19	10
31	25
45	50
55	75
63	100

by

Vagelis G. Papadakis

Chemical Engineer, PhD

Maria P. Efstathiou

Software Engineer, MSc

Patras, Greece, 2005

V.G. Papadakis & Associates

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V.G. Papadakis & Assoc.
Patras Science Park S.A.
Stadiou Str., Platani, GR-26504, Patras, Greece
Tel.: +30 2610 911571 & +30 6932 327323
Fax: +30 2610 911570 e-mail: vgp@psp.org.gr

Foreword

Deterioration of concrete in service may be the result of a variety of mechanical, physical, chemical or biological processes, with the c*orrosion of steel reinforcement* to be the most serious durability problem of the reinforced concrete structures. Over the past 50 years, an enormous amount of energy has been expended in laboratory and field studies on *concrete durability*. The results of this research are still either widely scattered in the journal literature or mentioned briefly in the standard textbooks. Moreover, the theoretical approaches of deterioration mechanisms with a predictive character are limited to some complicated mathematical models not widely applicable in practice.

A significant step forward is the present development of a *software package for computer estimation of the concrete service life* - EUCON®. This package is based on the most reliable mathematical models and is strengthened by adequate experimental data. The present work is the *user manual* of the EUCON® package and it aims to help essentially and to orient correctly the program user.

In the beginning, a *mix design strategy* to fulfil any requirements on strength and service life is presented. The *chemical and volumetric characteristics* of concrete are first estimated and the *service life of the concrete structure* is then predicted, based on fundamental models described analytically in the *theoretical background* [1]. The prediction is focused on the basic deterioration phenomena of the reinforced concrete, *carbonation and chloride penetration.* Aspects on *concrete strength* and *production cost* are also considered. The computer results enable mixture proportions to be accurately specified and concrete performance reliably predicted. The work structure presented herein is in full compliance with the new *European Standards for cement: EN 197 and concrete: EN 206.* The programming language used was the Microsoft® visual basic version 6.0.

The experimental research and mathematical modelling has been carried out mostly by Dr. Vagelis G. Papadakis as a part of various research projects, during the last 20 years. Mrs. Maria P. Efstathiou developed the computer program based on the above theoretical background. The

General Secretariat for Research and Technology, Ministry of Development, Greece, provided financial support for the present work through the PRAXE Programme (02-PRAXE-86).

Vagelis G. Papadakis
Maria P. Efstathiou
January 2005

Dr. *Vagelis G. Papadakis* holds a diploma in Chemical Engineering (1986) from the University of Patras, Greece, and a Ph.D. on the subject of carbonation and durability of concrete from the same institution (1990). He has a 20-year experience on scientific and demonstration projects on durability and technology of concrete, authored many papers and awarded by the American Concrete Institute (Wason Medal for Materials Research- 1993). He worked as a Researcher at the Danish Technological Institute, Building Technology Division, Concrete Centre (1997-1999) on supplementary cementing materials in concrete, holding an EU-fellowship (Marie Curie Grant). He was head of Concrete Technology Laboratory of TITAN Cement company S.A., Greece (1999-2000). During 2001-2006, he was head of "V.G. Papadakis & Associates – Building Technology and Durability" an innovative firm placed in "Patras Science Park S.A.", and, in parallel, a Research & Development Consultant in "Patras Science Park S.A" in the field of development, promotion and exploitation of Innovation. At the present (2007-) he is an Associate Professor in the Department of Environmental and Natural Resources Management, University of Ioannina, Greece.

Mrs. *Maria P. Efstathiou*, Software Engineer, holds a BSc in Computer Information Systems, from the American College of Greece (Deree College), and an MSc in Software Engineering Methods from the University of Essex, UK. She is specialized in numerical analysis, design and development of software applications in chemical and material engineering. During 2001-2006, she was a member of staff of the unit "V.G. Papadakis & Associates – Building Technology and Durability", Patras Science Park S.A., Greece. At the present, she is a Research Associate in "Patras Science Park S.A" and in management committee of "Regional Innovation Pole of Western Greece".

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1. WELCOME TO EUCON®

1.1 Introduction

In all concrete constructions besides the common strength problems, in presence or not of seismic activity, serious problems from environmental attack may be presented which decrease significantly their *durability and service lifetime*. In the literature there is a vast majority of papers dealing with the degradation mechanisms, attempting either to study them experimentally or to simulate them using fundamental or empirical models. The lots of experimental results and the complicated mathematical models on the other hand, make difficult their wide use from the concrete engineers. It is time all this information to be included in ***a software package,*** **where the user by giving the minimum required data will be receiving reliably the concrete mix design, ensuring the specified strength level and service lifetime, at the minimum cost.**

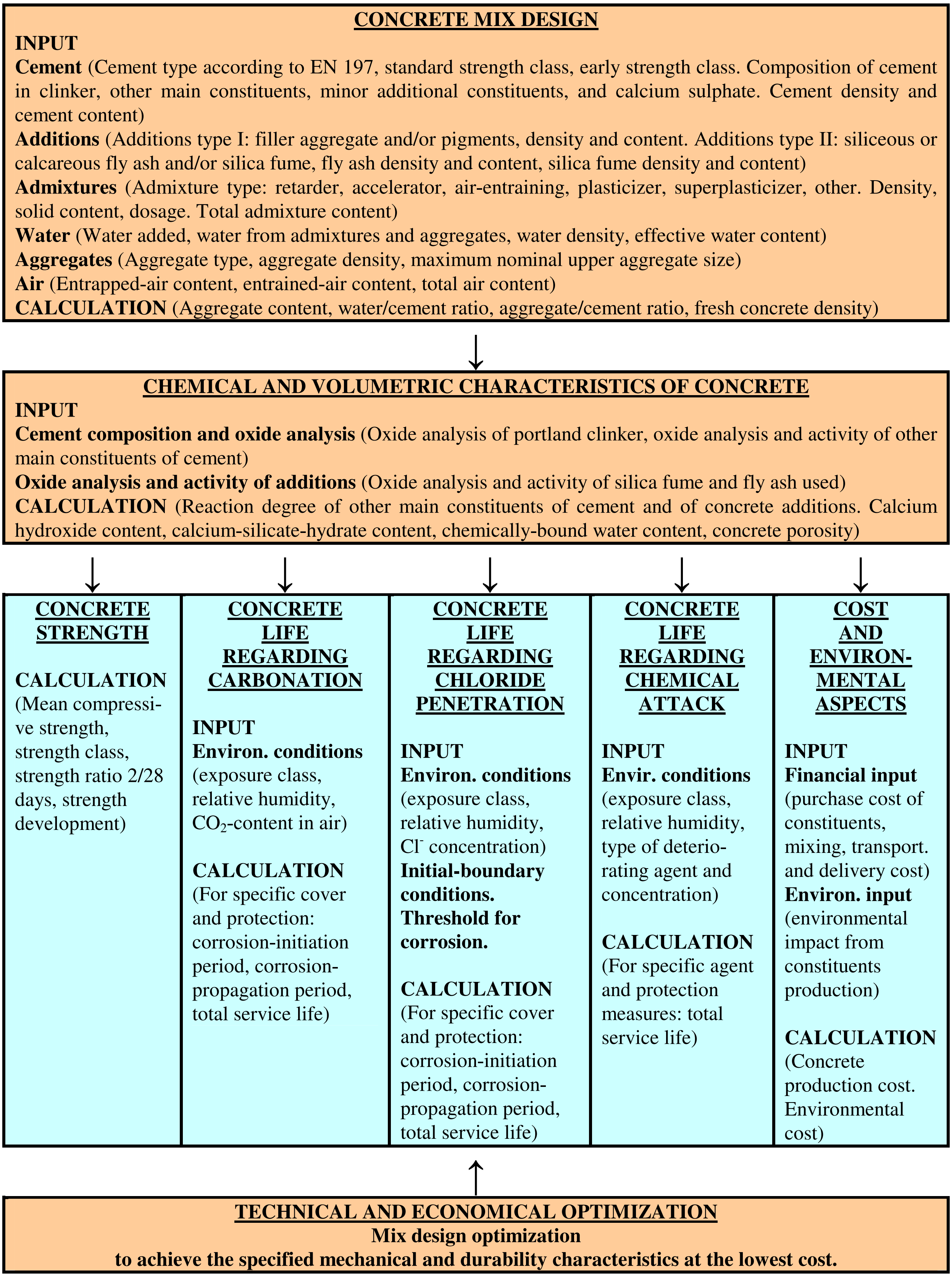
A such software package entitled ***EUCON®*** was developed by the present authors. Using this software an optimum concrete design can be achieved by estimating reliably the concrete strength, durability and production cost. **The base for the development of this computer modelling is presented in detail in a companion work: *the theoretical background* [1].** After the definition of mix design and structure characteristics, as well as an assumption regarding the environmental conditions where the structure will be found, the concrete service life can be reliably predicted using fundamental mathematical models that simulate the deterioration mechanisms and rate. The prediction is focused on the basic deterioration phenomena of the reinforced concrete, such as carbonation and chloride penetration, and on various chemical attacks. Aspects on concrete strength and production cost are also considered. This approach enable mixture proportions to be accurately specified and concrete performance reliably predicted. The work structure presented herein is in full compliance with the new ***European Standards for cement: EN 197*** [2] and ***for concrete: EN 206*** [3]. A general guidance on the use of alternative performance-related design methods (such as EUCON®) with respect to durability is already given in the European Standard EN 206 and it could be evolved in further generation standards.

1.2 Logical flowchart for concrete design

As given in [1], all *physical and mechanical mechanisms* for concrete deterioration, except direct loading and imposed deformations, may exhibit their effect on concrete performance during the first year of the service life. The *chemical and biological mechanisms* actually start from the early beginning; however, their detrimental results are observed after the first year. In reinforced concrete, the most serious deterioration mechanisms are those leading to corrosion of the reinforcement, which occurs after depassivation due to carbon dioxide or chloride ion penetration. Almost all other deterioration mechanisms can be controlled since the mix design and cast. It is therefore necessary the modelling attempts to turn towards the **corrosion initiation mechanisms and the chemical attack processes**.

In Fig. 1.2.1, the logical flowchart followed in the software package EUCON® for the estimation of concrete service life is presented. First, the essential parameters that characterize a concrete composition (**mix design**) are selected or calculated, and this is the main source on which all other concrete characteristics depend. Afterwards, the main **chemical and volumetric characteristics** of concrete are calculated (chemical composition of hydrated cementitious materials, porosity and related characteristics) and this is also another source to receive more information. Based on the selected mix design (cement type and strength class, cement content, water/cement ratio, air content, aggregates type, type and activity of additions, etc.), a first approximation of the **compressive strength class** of concrete is estimated [1].

For each significant deterioration mechanism, according to the specific environment where the structure would be found, an appropriate proven predictive model is used [1]. Concrete **carbonation and chloride penetration** are the most common causes for reinforcement corrosion and further concrete deterioration. The **service life of the structure** found in these environments that cause either carbonation or chloride attack is calculated. The degree of deterioration from a possible **chemical attack** is also estimated. Finally, **cost and environmental aspects** regarding concrete composition are full analysed. Now, for the initially selected concrete composition the most essential properties have been predicted, such as strength, service life and cost. The **designer** can then modify accordingly the concrete composition **to improve further** every required property.



CONCRETE MIX DESIGN

INPUT

Cement (Cement type according to EN 197, standard strength class, early strength class. Composition of cement in clinker, other main constituents, minor additional constituents, and calcium sulphate. Cement density and cement content)

Additions (Additions type I: filler aggregate and/or pigments, density and content. Additions type II: siliceous or calcareous fly ash and/or silica fume, fly ash density and content, silica fume density and content)

Admixtures (Admixture type: retarder, accelerator, air-entraining, plasticizer, superplasticizer, other. Density, solid content, dosage. Total admixture content)

Water (Water added, water from admixtures and aggregates, water density, effective water content)

Aggregates (Aggregate type, aggregate density, maximum nominal upper aggregate size)

Air (Entrapped-air content, entrained-air content, total air content)

CALCULATION (Aggregate content, water/cement ratio, aggregate/cement ratio, fresh concrete density)

CHEMICAL AND VOLUMETRIC CHARACTERISTICS OF CONCRETE

INPUT

Cement composition and oxide analysis (Oxide analysis of portland clinker, oxide analysis and activity of other main constituents of cement)

Oxide analysis and activity of additions (Oxide analysis and activity of silica fume and fly ash used)

CALCULATION (Reaction degree of other main constituents of cement and of concrete additions. Calcium hydroxide content, calcium-silicate-hydrate content, chemically-bound water content, concrete porosity)

CONCRETE STRENGTH

CALCULATION (Mean compressive strength, strength class, strength ratio 2/28 days, strength development)

CONCRETE LIFE REGARDING CARBONATION

INPUT

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

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

CONCRETE LIFE REGARDING CHLORIDE PENETRATION

INPUT

Environ. conditions (exposure class, relative humidity, Cl^- concentration) **Initial-boundary conditions. Threshold for corrosion.**

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

CONCRETE LIFE REGARDING CHEMICAL ATTACK

INPUT

Envir. conditions (exposure class, relative humidity, type of deteriorating agent and concentration)

CALCULATION (For specific agent and protection measures: total service life)

COST AND ENVIRONMENTAL ASPECTS

INPUT

Financial input (purchase cost of constituents, mixing, transport. and delivery cost) **Environ. input** (environmental impact from constituents production)

CALCULATION (Concrete production cost. Environmental cost)

TECHNICAL AND ECONOMICAL OPTIMIZATION

Mix design optimization

to achieve the specified mechanical and durability characteristics at the lowest cost.

Figure 1.2.1 Logical diagram for computer design of concrete mix for specified strength class, service life and cost.

1.3 Installation

Operating System:
The installation of EUCON is successfully carried out on computers that have one of the following operating systems: Windows 98/2000/XP or Windows NT.

Screen Resolution:
Screen Resolution must be at least 1024x768.

DPI Setting:
For the best display of EUCON interface, set the DPI setting of your computer to *Normal size (96 DPI).* To do this, do the following:

- Right-click on your desktop
- From the menu, click on *Display Properties*
- Click on the Tab *Settings*
- Click the button *Advanced*
- On the *General* Tab, set the *DPI setting* to *Normal size (96 DPI)*

Graphs:
For the successful creation of EUCON graphs, you computer must have installed Microsoft Office Excel.

Security:
To prevent piracy, the electronic key Sentinel™ UltraPro of SafeNet is used which is included in the EUCON package. The electronic key is attached to an available USB port of your computer, Fig. 1.3.1. When this is connected, the LED on the key is illuminated to verify that the key has been plugged-in properly.

*** Without the presence of the electronic key at the USB port, EUCON cannot be executed ***

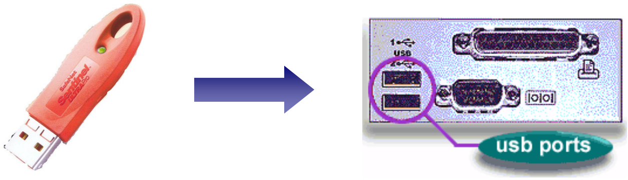


Fig 1.3.1 The electronic key UltraPro is attached to a USB port.

Note: USB UltraPro electronic key is not supported on computers whose operating system is Windows NT. In this case, the USB key is replaced with a parallel port key.

Installation:

- Insert the EUCON installation CD into the CD-ROM drive of your computer.
- The Setup Application will automatically run on your computer.
- If not, you will have to open the CD yourself and double-click on the file **Setup.exe**.
- Follow the suggested steps presented on your computer screen. If you wish, you may change them. At the end of the installation procedure you may be prompted to restart you computer.

After installation:
After the installation setup of EUCON is successfully completed, a folder *C:\Program Files\EUCON* will have been created containing all the necessary files for the proper execution of EUCON.

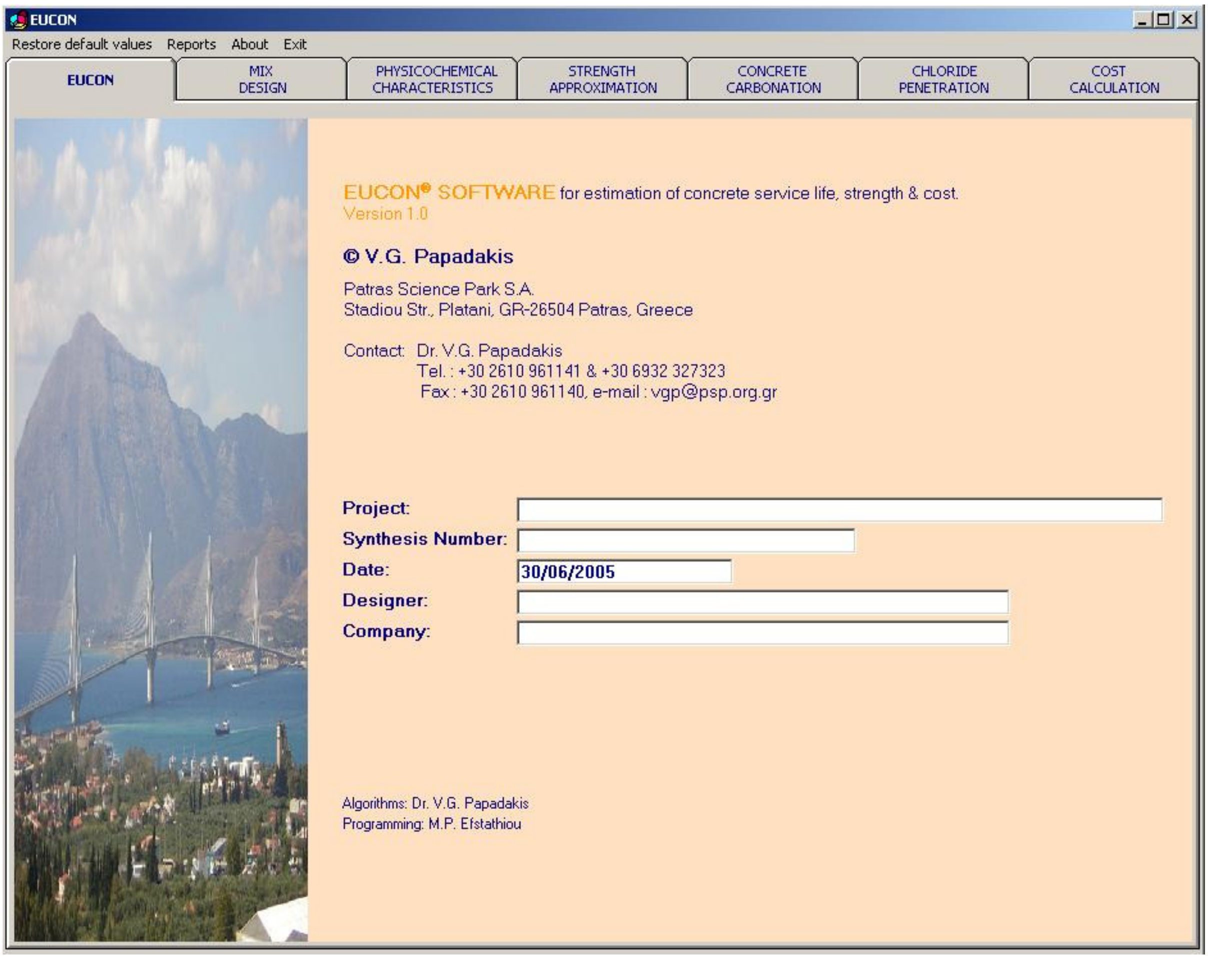
Execution:
First attach the electronic key to an available port of your computer. The first time you attach the key, the computer will need a couple of seconds to properly identify the new hardware device attached to it. Then you can start EUCON (Start→*Programs→eucon→EUCON).*

Note: The first time you execute a calculation, EUCON will need a couple of seconds to present the results. This is due to the configurations that need to take place between the application and the key.

Questions & Support:
For questions regarding EUCON, please contact: Dr. V.G. Papadakis
T: +30 2610 911571, **F**: +30 2610 911570, **E**: vgp@psp.org.gr

1.4 How to use EUCON®

The program EUCON® was developed on the logical flowchart presented in section 1.2, and a general view is given as Fig. 1.4.1. The program is divided into several **tabs**, each of them performs specific calculations. These tabs **have to be used in a successive way**, as follows.



EUCON® SOFTWARE for estimation of concrete service life, strength & cost.
Version 1.0

© V.G. Papadakis

Patras Science Park S.A.
Stadiou Str., Platani, GR-26504 Patras, Greece

Contact: Dr. V.G. Papadakis
Tel. : +30 2610 961141 & +30 6932 327323
Fax : +30 2610 961140, e-mail : vgp@psp.org.gr

Project:
Synthesis Number:
Date: 30/06/2005
Designer:
Company:

Algorithms: Dr. V.G. Papadakis
Programming: M.P. Efstathiou

Figure 1.4.1 General overview of EUCON® program showing its cover page and the main tabs for the individual estimations.

In the **cover-1st tab**, the **general information** for the project under examination may be introduced (*optional tab*). This includes the identification of the project, the serial number of the trial concrete mix, the present date, and the names of the designer and the company that undertake the design study.

The **2nd tab** concerns data and calculation for the **concrete mix design,** and together with the **3rd tab** that calculates the **chemical and volumetric composition** of the concrete, are basic tasks that all other calculations are depend on (*mandatory tabs* that have to be used initially in a successive way: first the tab for mix design and then the tab for chemical and volumetric composition).

All other remaining tabs, i.e., the **4th tab** for **strength approximation**, the **5th tab** for **estimation of service life regarding concrete carbonation**, the **6th tab** for **estimation of service life regarding chloride penetration**, and the **7th tab** for **cost estimations**, are based on the previous two tabs and they can be used independently in order to estimate each specific characteristic they deal with.

All tabs contain:

- a field that the user introduces the **data** (default values that can change from the user: the *"white boxes"*, dependent variables that cannot change: the *"yellow boxes"*),
- a **calculation button**, and
- a field of the **results** (*"orange boxes"* with results in *blue bold colour* that cannot change).

Finally, there are separate actions such as **save, clear, reports, help, about, exit**, that can be used in order, respectively, to save the introduced data as default, to return to the default values, to create a report file or to print, to guide the user, to give general information and, finally, to exit.

All tabs and actions are described in detail in the sequence.

2. MIX DESIGN

2.1 General

Concrete is the material formed by mixing cement, aggregates and water, with or without the incorporation of admixtures and additions, which develops its properties by hydration of the cement. The general concept for concrete mix design as presented herein is in full compliance with the most spread existing standards for concrete production, such as the *European Standard for concrete: EN 206* [3]. For the present application, a concrete volume is assumed that contains certain amounts of ***cement, additions (optional), aggregates, water, and admixtures (optional)*** *only*, see Fig. 2.1.1. To the above materials ***entrained or entrapped air*** should be added.

CONCRETE :

Cement: main constituents: portland clinker, blast furnace slag, silica fume, pozzolanic materials (natural or natural calcined pozzolanas), fly ash (siliceous or calcareous), burnt shale, and limestone
minor additional constituents: all main constituents except clinker
calcium sulphate, additives

+

Additions: type I (filler aggregate, pigments), type II (fly ash, silica fume)

+

Aggregates: fine, coarse

+

Water: mixing water

+

Admixtures: retarder, accelerator, air-entraining, plasticizer, superplasticizer, etc.

+

Air: entrained, entrapped

Figure 2.1.1 Constituent materials for concrete composition.

All these materials have to comply with the corresponding standards for the constituent materials, for instance in the case of European Standards: EN 197 (Cement), EN 450 (Fly ash for concrete), EN 13263 (Silica fume for concrete), EN 12620 (Aggregates for concrete), EN 1008 (Mixing water for concrete), EN 934-2 (Admixtures for concrete), etc.

In Fig. 2.1.2, the part (tab) of the logical flowchart of EUCON® for the desing of the concrete mix is presented. The tab contains:

- a field that the user introduces the **input data** for cement, additions, admixtures, water, aggregates, and air.
- a **calculation button**, and
- a field of the **output results** including the *aggregate content* in order to achieve the mass balance requirements.

CONCRETE MIX DESIGN

INPUT

Cement (Cement type according to EN 197, standard strength class, early strength class. Composition of cement in clinker, other main constituents, minor additional constituents, and calcium sulphate. Cement density and cement content)

Additions (Additions type I: filler aggregate and/or pigments, density and content. Additions type II: siliceous or calcareous fly ash and/or silica fume, fly ash density and content, silica fume density and content)

Admixtures (Admixture type: retarder, accelerator, air-entraining, plasticizer, superplasticizer, other. Density, solid content, dosage. Total admixture content)

Water (Water/cement ratio, effective water content, water from admixtures, water added, water density)

Aggregates (Aggregate type, maximum nominal upper aggregate size, aggregate density)

Air (Entrapped-air content, entrained-air content, total air content)

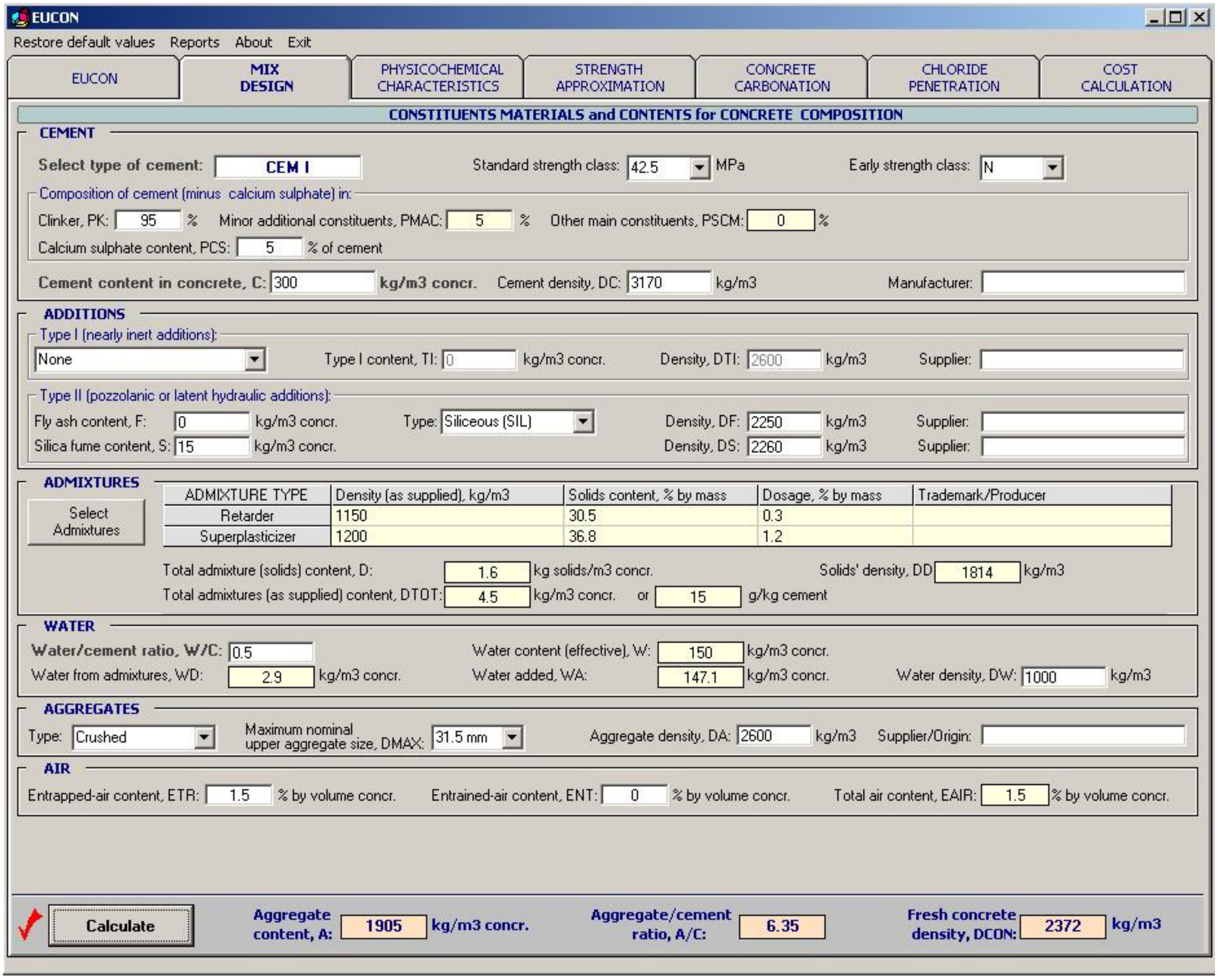
▼

CALCULATION

(Aggregate content, aggregate/cement ratio, fresh concrete density)

Figure 2.1.2 Logical diagram for computer design of concrete mix.

A general view of this tab is given as Fig. 2.1.3. The user has to fill in the "white boxes" (where applicable) and then to press the calculation button in order to complete the mix proportioning for the concrete. For the algebraic formulae used for these calculations and further questions, **please always advise the *Theoretical Background* [1], chapter 2**. In the sequence, each part of this tab is discussed in detail.



CONSTITUENTS MATERIALS and CONTENTS for CONCRETE COMPOSITION

CEMENT

Select type of cement: CEM I
Standard strength class: 42.5 MPa
Early strength class: N

Composition of cement (minus calcium sulphate) in:
Clinker, PK: 95 %
Minor additional constituents, PMAC: 5 %
Other main constituents, PSCM: 0 %
Calcium sulphate content, PCS: 5 % of cement

Cement content in concrete, C: 300 **kg/m3 concr.**
Cement density, DC: 3170 kg/m3
Manufacturer:

ADDITIONS

Type I (nearly inert additions):
None
Type I content, TI: 0 kg/m3 concr.
Density, DTI: 2600 kg/m3
Supplier:

Type II (pozzolanic or latent hydraulic additions):
Fly ash content, F: 0 kg/m3 concr.
Type: Siliceous (SIL)
Density, DF: 2250 kg/m3
Supplier:
Silica fume content, S: 15 kg/m3 concr.
Density, DS: 2260 kg/m3
Supplier:

ADMIXTURES

ADMIXTURE TYPE	Density (as supplied), kg/m3	Solids content, % by mass	Dosage, % by mass	Trademark/Producer
Retarder	1150	30.5	0.3	
Superplasticizer	1200	36.8	1.2	

Total admixture (solids) content, D: 1.6 kg solids/m3 concr.
Solids' density, DD: 1814 kg/m3
Total admixtures (as supplied) content, DTOT: 4.5 kg/m3 concr. or 15 g/kg cement

WATER

Water/cement ratio, W/C: 0.5
Water content (effective), W: 150 kg/m3 concr.
Water from admixtures, WD: 2.9 kg/m3 concr.
Water added, WA: 147.1 kg/m3 concr.
Water density, DW: 1000 kg/m3

AGGREGATES

Type: Crushed
Maximum nominal upper aggregate size, DMAX: 31.5 mm
Aggregate density, DA: 2600 kg/m3
Supplier/Origin:

AIR

Entrapped-air content, ETR: 1.5 % by volume concr.
Entrained-air content, ENT: 0 % by volume concr.
Total air content, EAIR: 1.5 % by volume concr.

Aggregate content, A: 1905 **kg/m3 concr.**
Aggregate/cement ratio, A/C: 6.35
Fresh concrete density, DCON: 2372 **kg/m3**

Figure 2.1.3 General view of the tab "MIX DESIGN" of the EUCON® program.

2.2 Cement

Cement identification

Cement type:	By clicking on the near "white box", a "select cement type" window opens. Click on the cement main type (CEM I, CEM II, CEM III, CEM IV or CEM V) that you want to use in the mix, select the exact cement type, and click on the button "**v**" to introduce it into the mix (always advise Table 2.2.1 for cement notation according to EN 197-1 [2]). LIMITS: You have to select a cement type from the open window exclusively. If the construction is an old one and a past cement type might be used, or another cement standard is applied, or more than one cement used, then you have to select the closest cement type from the 27 types existing on EN 197, and to adjust the composition. DEFAULT VALUE: CEM I
Standard strength class:	Use the button "▼" and select the standard strength class of cement according to EN 197-1 and EN 196-1. UNITS: MPa LIMITS: You have to select among the values 32.5, 42.5, and 52.5 MPa, only. It has a significant effect on 28-days strength. If another cement standard is applied, then you have to select the closest cement's standard strength class from the above. DEFAULT VALUE: 42.5 MPa
Early strength class:	Use the button "▼" and select the early strength class of cement according to EN 197-1 and EN 196-1. LIMITS: You have to select among the values N (ordinary early strength) and R (high early strength), only. It has a significant effect on 2- and 7-days strength. If another cement standard is applied, then you have to select the closest cement's early strength class from the above. DEFAULT VALUE: N
Manufacturer (optional)	The name of the cement manufacturer.

Table 2.2.1 Types of common cements according to European Standard EN 197-1*.

Main types	Notation	Main constituents**									Minor addit. const.
		K	**S**	**D**	**P**	**Q**	**V**	**W**	**T**	**L/LL**	
PORTLAND CEMENTS											
CEM I	I	95-100	-	-	-	-	-	-	-	-	0-5
PORTLAND-COMPOSITE CEMENTS											
CEM II	II/A-S	80-94	6-20	-	-	-	-	-	-	-	0-5
	II/B-S	65-79	21-35	-	-	-	-	-	-	-	0-5
	II/A-D	90-94	-	6-10	-	-	-	-	-	-	0-5
	II/A-P	80-94	-	-	6-20	-	-	-	-	-	0-5
	II/B-P	65-79	-	-	21-35	-	-	-	-	-	0-5
	II/A-Q	80-94	-	-	-	6-20	-	-	-	-	0-5
	II/B-Q	65-79	-	-	-	21-35	-	-	-	-	0-5
	II/A-V	80-94	-	-	-	-	6-20	-	-	-	0-5
	II/B-V	65-79	-	-	-	-	21-35	-	-	-	0-5
	II/A-W	80-94	-	-	-	-	-	6-20	-	-	0-5
	II/B-W	65-79	-	-	-	-	-	21-35	-	-	0-5
	II/A-T	80-94	-	-	-	-	-	-	6-20	-	0-5
	II/B-T	65-79	-	-	-	-	-	-	21-35	-	0-5
	II/A-L	80-94	-	-	-	-	-	-	-	6-20	0-5
	II/B-L	65-79	-	-	-	-	-	-	-	21-35	0-5
	II/A-M	80-94	6-20								0-5
	II/B-M	65-79	21-35								0-5
BLASTFURNACE CEMENTS											
CEM III	III/A	35-64	36-65	-	-	-	-	-	-	-	0-5
	III/B	20-34	66-80	-	-	-	-	-	-	-	0-5
	III/C	5-19	81-95	-	-	-	-	-	-	-	0-5
POZZOLANIC CEMENTS											
CEM IV	IV/A	65-89	-	11-35					-	-	0-5
	IV/B	45-64	-	36-55					-	-	0-5
COMPOSITE CEMENTS											
CEM V	V/A	40-64	18-30	-	18-30			-	-	-	0-5
	V/B	20-38	31-50	-	31-50			-	-	-	0-5

* The composition is expressed as % by mass of the main and minor additional constituents.

** Notation **exclusively** for the present table: portland clinker (K), blast furnace slag (S), silica fume (D), pozzolana (natural, P or natural calcined, Q), various fly ashes (siliceous, V or calcareous, W), burnt shale (T), and limestone (L or LL).

Cement composition

Clinker, PK:	The percentage of clinker (including the various additives) in the cement (minus calcium sulphate). You may change the default value, within the permitted range, if you have an accurate composition from the cement manufacturer. UNITS: % by mass LIMITS: given in the column K of Table 2.2.1, according to the cement type used. DEFAULT VALUE: the lower limit in the column K of Table 2.2.1, plus 10 for all CEM III, CEM IV/B, and all CEM V.
Minor additional constituents, PMAC:	The percentage of minor additional constituents in the cement (minus calcium sulphate). You may change the default value, within the permitted range, if you have an accurate composition. For CEM I you may change this value by changing accordingly the PK. UNITS: % by mass LIMITS: 0-5%, except CEM II/A-D, where it is 0-4% DEFAULT VALUE: 5 %, except CEM II/A-D, CEM III, where it is 4%
Other main constituents, PSCM:	The percentage of supplementary cementing materials (SCM) in the cement (minus calcium sulphate). It shall be: (PSCM = 100 – PK – PMAC), and thus is not permitted to write on (“yellow box”) in order to ensure mass balance satisfaction. You may change this value, within the permitted range, by changing accordingly the PK and PMAC. In the case of cement type CEM V, these composite cements contain, apart the clinker, certain amounts of both slag and other pozzolanic materials, and then the PSCM is separated in **PSL** (%), referring to slag percentage in cement, and **PPO** = (PSCM – PSL), referring to the other pozzolanic materials. UNITS: % by mass LIMITS: given in the column of main constituents, but K, on the Table 2.2.1, according to the cement type used. DEFAULT VALUE: that calculated from the equation (PSCM = 100 – PK – PMAC), using the default values for PK and PMAC.
Calcium	The percentage of calcium sulphate in the cement. You may change the

sulphate content, PCS:	default value, within the permitted range, if you have an accurate one from the cement manufacturer. UNITS: % by mass LIMITS: 1-10% DEFAULT VALUE: 5 %

Cement content and density

Cement content, C:	Introduce the total cement content in the concrete volume. UNITS: kg cement / m^3 of concrete LIMITS: $0<C<DC$ DEFAULT VALUE: 300 kg/m^3
Cement density, DC:	Introduce the particle density of cement. UNITS: kg/m^3 LIMITS: 2000 – 4000 kg/m^3 DEFAULT VALUE: $DC = 3200 (PK/100) + 2600 (100 – PK)/100$

2.3 Additions

Type I (nearly inert additions)

Type I:	Use the button "▼" and select the type I addition (nearly inert). LIMITS: choose between none, filler aggregate conforming to EN 12620, pigments conforming to EN 12878, or both filler aggregate and pigments. DEFAULT VALUE: No
Type I content, TI:	Introduce the Type I additions' content in the concrete volume. UNITS: kg Type I addition / m^3 of concrete LIMITS: $0\leq TI<DTI$ DEFAULT VALUE: 0 kg/m^3
Type I density, DTI:	Introduce the particle density of Type I additions. UNITS: kg/m^3 LIMITS: 1000 - 4000

	DEFAULT VALUE: 2600 kg/m^3
Supplier (optional)	The name of the Type I additions' supplier.

Type II (pozzolanic or latent hydraulic additions)

Fly ash content, F:	Introduce the fly ash content in the concrete volume. Fly ash shall conform to EN 450 or a European Technical Approval, or a relevant national standard or provisions. We suppose that *when a type II addition is used directly in concrete, only a cement type CEM I is permitted.* UNITS: kg fly ash / m^3 of concrete LIMITS: $0 \leq F < DF$ DEFAULT VALUE: 0 kg/m^3
Fly ash type:	Use the button "▼" and select the fly ash type. LIMITS: choose between siliceous and calcareous fly ash. DEFAULT VALUE: siliceous fly ash
Fly ash density, DF:	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
Supplier (optional)	The name of the fly ash supplier.

Silica fume content, S:	Introduce the silica fume content in the concrete volume. Silica fume shall conform to EN 13263 or a European Technical Approval, or a relevant national standard or provisions. We suppose that *when a type II addition is used directly in concrete, only a cement type CEM I is permitted.* UNITS: kg silica fume / m^3 of concrete LIMITS: $0 \leq S < DS$ DEFAULT VALUE: 0 kg/m^3
Silica fume	Introduce the particle density of silica fume.

density, DS:	UNITS: kg/m^3 LIMITS: 1500 - 4000 DEFAULT VALUE: 2260 kg/m^3
Supplier (optional)	The name of the silica fume supplier.

2.4 Admixtures

Select admixture types:	By clicking on the near box, a “select admixture types” window opens. By using the arrow “→”, select between none and available armixture types that you want to use in the mix. By using the arrow “←”, remove your selection. In this window you can introduce the admixture density, solids content, dosage and trademark/producer (admixtures shall conform to EN 934-2, default values given below). Click on the button “**v**” to entry your final selection and values. Click on the same box if you want to alter a selection or to correct an admixture characteristic. LIMITS: You have to select none, one or more admixture types from the open window exclusively. You may select an “other type” that you may specify, accordingly. DEFAULT VALUE: None

Admixture type	**Density (as supplied)** kg/m^3	**Solids content,** % by mass	**Dosage,** % by mass cement
None	-	-	0
Retarder	1150	30.5	0.3 (0.2-0.4)
Accelerator	1200	32.0	3.5 (0.5-6)
Air-entraining	1030	12.0	0.10 (0.05-0.2)
Plasticizer	1180	32.0	0.4 (0.3-0.5)
Superplasticizer	1200	36.8	1.2 (0.8-1.5)
Other	1200	32.0	0.5
Total admixture	The total admixture (only solids) content in the concrete volume. It is		

(solids) content, D:	indirectly estimated from the dosages and characteristics of the various admixtures. UNITS: kg admixture solids / m^3 of concrete LIMITS: The total amount of each admixture, if any, shall not exceed the *maximum dosage* recommended by the admixture producer. DEFAULT VALUE: 0 kg/m^3
Total admixtures (as supplied) content, DTOT:	The total admixture (solids and water) content in the concrete volume. It is indirectly estimated from the dosages and characteristics of the various admixtures. UNITS: kg solution / m^3 of concrete or g /kg cement LIMITS: not exceed 50 g of admixture (as supplied) per kg cement unless the influence of the higher dosage on the performance and durability is established. DEFAULT VALUE: 0 kg/m^3
Solids' density, DD:	The solids' density of the admixtures. It is indirectly estimated from the density and solids content of the various admixtures. UNITS: kg/m^3 DEFAULT VALUE: 1800 kg/m^3

2.5 Water

Water/cement ratio, W/C:	Introduce the ratio of the effective water content to cement content by mass in the fresh concrete. UNITS: dimensionless LIMITS: 0.2 – 1.5 DEFAULT VALUE: 0.5
Water content (effective), W:	It is calculated as (W/C)C. If you want to change it, you have to change the water to cement ratio, W/C. UNITS: kg / m^3 of concrete DEFAULT VALUE: 150 kg/m^3
Water from	The total water content from admixtures in the concrete volume. It is

admixtures, WD:	indirectly estimated from the dosages and characteristics of the various admixtures. UNITS: kg / m^3 of concrete DEFAULT VALUE: 0 kg/m^3
Water added, WA:	It is calculated as (W-WD). It is the water that you add to the concrete volume (the mixing water shall conform to EN 1008) including the added water, plus water already contained on the surface of aggregates, plus water in the additions used in the form of a slurry, and water resulting from any added ice or steam heating. The water from admixtures is estimated separately before. UNITS: kg / m^3 of concrete DEFAULT VALUE: 150 kg/m^3
Water density, DW:	Introduce the water density. UNITS: kg/m^3 LIMITS: 900 - 1200 DEFAULT VALUE: 1000 kg/m^3

2.6 Aggregates

Aggregate type:	Use the button "▼" and select the aggregate type. Normal and heavy-weight aggregates are supposed conforming to EN 12620. LIMITS: choose between crushed or rounded. This selection has an effect on concrete strength. DEFAULT VALUE: crushed
Maximum nominal upper aggregate size, DMAX:	Use the button "▼" and select this size, taking into account the concrete cover to reinforcement and the minimum section width. UNITS: mm LIMITS: choose between these values 8, 16, 31.5, 63 mm. This selection has an effect on entrapped-air content and further on strength. DEFAULT VALUE: 31.5 mm
Aggregate	Introduce the particle density of aggregates.

density, DA:	UNITS: kg/m^3 LIMITS: 1000 - 4000 DEFAULT VALUE: 2600 kg/m^3
Supplier/ Origin (optional)	The name of the aggregates’ supplier or origin.

2.7 Air

Entrapped-air content, ETR:	The voids in concrete which are not purposely entrained. It is estimated from the maximum nominal upper aggregate size (data from ACI): *DMAX (mm)* *ETR (%)* 8 3.5 19 2.3 31.5 1.5 63 0.4 The above values assume that the concrete is properly placed and compacted in accordance with ENV 13670 or other relevant standards. However, this value can be change if a poor compaction takes place, and appropriate experimental results can be obtained. UNITS: % volume air /volume concrete LIMITS: 0.1-15%. This selection has an effect on strength and durability. DEFAULT VALUE: 1.2%
Entrained-air content, ENT:	The microscopic air bubbles intentionally incorporated in concrete during mixing, usually by use of a air-emtraining agent. It is estimated from the air-entraining dosage as follows (data from manufacturers): $ENT\ (\%) = 17.8\ (dosage,\ \%\ by\ mass\ cement)^{0.5}$ However, this value can be change, if you have more accurate results from the admixture provider. UNITS: % volume air /volume concrete LIMITS: 0-15%. This selection has an effect on strength and durability.

	DEFAULT VALUE: 0%
Air content, EAIR:	The total entrained and entrapped air content of concrete, when compacted in accordance with the procedure given in EN 12350-6. It shall be measured in accordance with EN 12350-7. Here is the sum of ETR + ENT. If you want to change it you have to change accordingly the ETR or ENT. UNITS: % volume air /volume concrete LIMITS: 0.1-15%. DEFAULT VALUE: 1.2%

2.8 Calculations

As the **basis** for concrete composition, the volume unit of **1 m^3** of the fresh concrete is selected. By assuming negligible expansion, this volume unit represents also hardened concrete. It must be emphasized that if *a material is added* to this unit, *then an equal volume of another component must be removed* in order to keep the same total volume and a common comparison basis. The following mass balance equation has to be fulfilled:

$$C/DC + TI/DTI + S/DS + F/DF + A/DA + W/DW + D/DD + EAIR/100 = 1 \qquad (2.8.1)$$

This Eq. (2.2.1) may be used to calculate the *aggregate content* if all other composition parameters are known:

$$A = (1 - C/DC - TI/DTI - S/DS - F/DF - W/DW - D/DD - EAIR/100)\ DA \qquad (2.8.2)$$

The *fresh concrete density*, DCON (kg/m^3), is given by:

$$d_{CON} = C + TI + S + F + A + W + D \qquad (2.8.3)$$

click on the "Calculate" button to estimate:

Aggregate content, A:	The total aggregate content in the concrete volume. We suppose that the aggregates are internal saturated by water and their surface is dry. UNITS: kg aggregate / m^3 of concrete DEFAULT VALUE: 1933 kg/m^3
Aggregate/cement ratio, A/C:	The ratio of the aggregate content to cement content by mass in the fresh concrete. UNITS: dimensionless DEFAULT VALUE: 6.44
Fresh concrete density, DCON:	The weight of fresh concrete per concrete volume. UNITS: kg/m^3 DEFAULT VALUE: 2383 kg/m^3

By obtaining the above concrete composition (mix design) you may:

- **accept this composition** and continue in the next tab “Physicochemical Characteristics” and further …
- otherwise, **you may change any input data** in order to correct the output results of this tab, **until final acceptance.**
- Always, you may change this composition when you want to improve a concrete property (strength, durability, cost).

3. PHYSICOCHEMICAL CHARACTERISTICS

3.1 General

In Fig. 3.1.1, the part (tab) of the logical flowchart of EUCON® for the calculation of the chemical and volumetric composition of concrete is presented. The tab contains:

- a field that the user introduces the **input data** for cement composition and oxide analysis, and additions activity and oxide analysis.
- a **calculation button**, and
- a field of the **output results** including the reaction degree of supplementary cementing materials and the various additions, the calcium hydroxide content and the concrete porosity.

CHEMICAL AND VOLUMETRIC CHARACTERISTICS OF CONCRETE

INPUT

Tab "MIX DESIGN" data

Cement composition and oxide analysis (Oxide analysis of portland clinker, oxide analysis and activity of other main constituents of cement)

Oxide analysis and activity of additions (Oxide analysis and activity of silica fume and fly ash used)

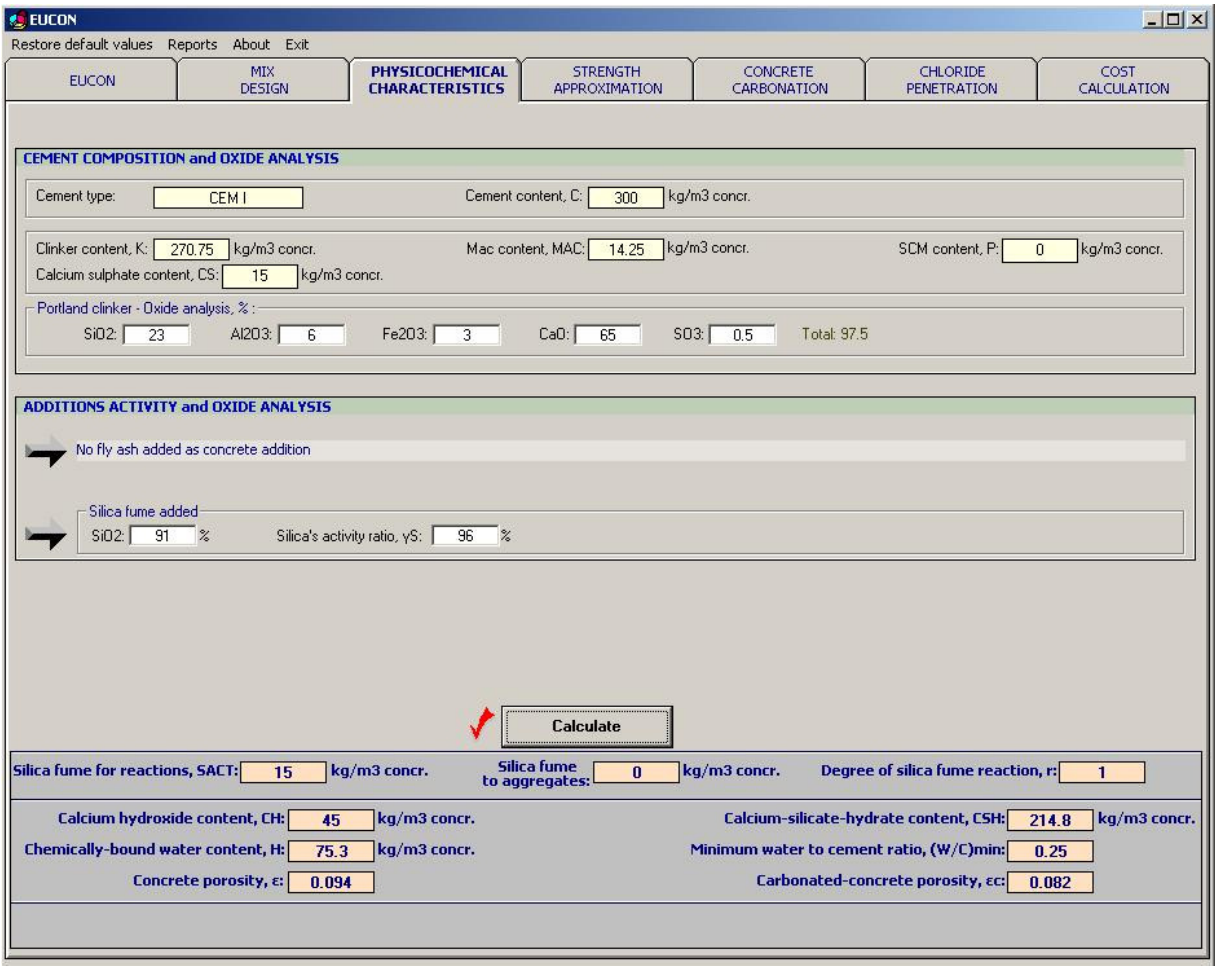
▼

CALCULATION

(Reaction degree of other main constituents of cement and of concrete additions. Calcium hydroxide content, calcium-silicate-hydrate content, chemically-bound water content, concrete porosity)

Figure 3.1.1 Logical diagram for computer calculation of the main chemical and volumetric characteristics of concrete.

A general view of this tab is given as Fig. 3.1.2. The user has to fill in the “white boxes” or to accept the default values, and then to press the calculation button in order to calculate the chemical and volumetric characteristics of concrete. For the algebraic formulae used for these calculations and further questions, **please always advise the *Theoretical Background* [1], chapter 3**. In the sequence, each part of this tab is discussed in detail.



CEMENT COMPOSITION and OXIDE ANALYSIS

Cement type: CEM I

Cement content, C: 300 kg/m3 concr.

Clinker content, K: 270.75 kg/m3 concr.

Mac content, MAC: 14.25 kg/m3 concr.

SCM content, P: 0 kg/m3 concr.

Calcium sulphate content, CS: 15 kg/m3 concr.

Portland clinker - Oxide analysis, % :

SiO2: 23
Al2O3: 6
Fe2O3: 3
CaO: 65
SO3: 0.5
Total: 97.5

ADDITIONS ACTIVITY and OXIDE ANALYSIS

No fly ash added as concrete addition

Silica fume added

SiO2: 91 %
Silica's activity ratio, γS: 96 %

Silica fume for reactions, SACT: 15 **kg/m3 concr.**

Silica fume to aggregates: 0 **kg/m3 concr.**

Degree of silica fume reaction, r: 1

Calcium hydroxide content, CH: 45 **kg/m3 concr.**

Calcium-silicate-hydrate content, CSH: 214.8 **kg/m3 concr.**

Chemically-bound water content, H: 75.3 **kg/m3 concr.**

Minimum water to cement ratio, (W/C)min: 0.25

Concrete porosity, ε: 0.094

Carbonated-concrete porosity, εc: 0.082

Figure 3.1.2 General view of the tab “PHYSICOCHEMICAL CHARACTERISTICS” of the EUCON® program.

3.2 Cement composition and oxide analysis

Cement composition

Cement type:	It is a reminder for the cement type used (see tab "MIX DESIGN").
Cement content, C:	It is a reminder for the total cement content in the concrete volume, kg/m^3 (see tab "MIX DESIGN").
Clinker content, K:	The absolute clinker content (including the various additives) in the concrete volume. It is calculated as [(PK/100) C (100-PCS)/100]. UNITS: kg/m^3 concrete
Minor additional constituents content, MAC:	The absolute content of minor additional constituents (mac) in the concrete volume. It is calculated as [(PMAC/100) C (100-PCS)/100]. UNITS: kg/m^3 concrete
Other main constituents (SCM) content, P:	The absolute content of the other main constituents (supplementary cementing materials- SCM) in the concrete volume. It is calculated as [(PSCM/100) C (100-PCS)/100]. In the case of cement type CEM V, these composite cements contain, apart the clinker, certain amounts of both slag and other pozzolanic materials, and then the SCM is separated in **SL** =[(PSL/100) C (100-PCS)/100], referring to slag content in the concrete, and **P** =[(PPO/100) C (100-PCS)/100], referring to the other pozzolanic materials content in the concrete. UNITS: kg/m^3 concrete
Calcium sulphate content, CS:	The absolute content of the calcium sulphate in the concrete volume. It is calculated as [(PCS/100) C]. UNITS: kg/m^3 concrete

Oxide analysis and activity

Portland clinker – Oxide analysis, %:	Introduce here the chemical analysis of portland clinker in terms of oxides: SiO_2, Al_2O_3, Fe_2O_3, CaO, and SO_3. Use the default values, if you do not have a more accurate oxide analysis. UNITS: % by mass LIMITS: the total sum of the oxides ≤ 100 DEFAULT VALUES: These in Table 3.2.1

Other main constituents in cement (SCM) – Oxide analysis, %:	It gives first the name of the other main constituent used in cement production. Introduce here its chemical analysis in terms of oxides: SiO_2, Al_2O_3, Fe_2O_3, CaO, and SO_3. Use the default values, if you do not have a more accurate oxide analysis. UNITS: % by mass LIMITS: the total sum of the oxides ≤ 100 DEFAULT VALUES: These in Table 3.2.1
Silica's activity ratio, γS: **Alumina's activity ratio, γA:**	Introduce here the percentage of the oxide SiO_2 or Al_2O_3 in the SCM, which contributes to the pozzolanic reactions (the glass or amorphous phase). Use the default values, if you do not have a more accurate result. UNITS: % by mass LIMITS: $0 \leq \gamma \leq 100$ DEFAULT VALUE: These in Table 3.2.1

Table 3.2.1 Typical oxide analysis (%) and activity ratios, γ (%), of portland clinker, silica fume, siliceous and calcareous fly ashes, and various SCM used in EN 197 (data from [1]).

	Cementitious/pozzolanic materials	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**SO_3**	**γS/γA**
1	Portland clinker	23	6	3	65	0.5	-
2	Blast furnace slag	36	9	1	40	0.5	90
3	Silica fume	91	1	1.5	0.7	0.4	96
4	Pozzolana (natural)	58	15	5	6	1	50
5	Pozzolana (natural, calcined)	53	42	1	0.1	0	80
6	Siliceous fly ash	53	20	9	4	0.6	82
7	Calcareous fly ash	39	16	6	24	4.3	71
8	Burnt shale	38	10	6	35	5	90
9	Limestone	2	1	0.2	2	0.1	50
10	Various SCM for CEM II	50	16	7	12	1.5	65
11	Various SCM for CEM IV	50	20	7	10	1	65
12	Various SCM for CEM V	50	20	7	10	1	65

3.3 Additions activity and oxide analysis

This field of data appears in the case of the use of additions such as fly ash (siliceous or calcareous) and/or silica fume. Otherwise, an indication of non-use of these materials appears.

Fly ash added

Oxide analysis, %:	It gives first the name of the fly ash (siliceous or calcareous) added as addition in concrete production. Introduce here the fly ash chemical analysis in terms of oxides: SiO_2, Al_2O_3, Fe_2O_3, CaO, and SO_3. Use the default values, if you do not have a more accurate oxide analysis. UNITS: % by mass LIMITS: the total sum of the oxides ≤ 100 DEFAULT VALUES: These in Table 3.2.1
Silica's activity ratio, γS: **Alumina's activity ratio, γA:**	Introduce here the percentage of the oxide SiO_2 or Al_2O_3 in the SCM, which contributes to the pozzolanic reactions (the glass or amorphous phase). Use the default values, if you do not have a more accurate result. UNITS: % by mass LIMITS: $0 \leq \gamma \leq 100$ DEFAULT VALUE: These in Table 3.2.1

Silica fume added

Oxide analysis, %:	Introduce here the total SiO_2 content in the silica fume. Use the default value, if you do not have a more accurate result. UNITS: % by mass LIMITS: $0 \leq SiO_2 \leq 100$ DEFAULT VALUE: This in Table 3.2.1
Silica's activity ratio, γS:	Introduce here the percentage of the oxide SiO_2 in the silica fume, which contributes to the pozzolanic reactions (the glass or amorphous phase). Use the default value, if you do not have a more accurate result. UNITS: % by mass LIMITS: $0 \leq \gamma S \leq 100$ DEFAULT VALUE: This in Table 3.2.1

3.4 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 3**. Click on the "**Calculate**" button to estimate:

the reaction degree of SCM and additions:

SCM for reactions:	The amount of SCM (other main constituents of cement, fly ash or silica fume as additions) that can participate in the pozzolanic reactions (active part). UNITS: kg / m^3 of concrete
SCM to aggregates:	The amount of SCM (other main constituents of cement, fly ash or silica fume as additions) that cannot participate in the pozzolanic reactions and thus may be included to the aggregates (inert part). UNITS: kg / m^3 of concrete
Degree of SCM reaction, r:	The ratio of SCM (other main constituents of cement, fly ash or silica fume as additions) for reactions to the total SCM content. UNITS: dimensionless LIMITS: $0 \leq r \leq 1$

the main chemical composition of concrete (final):

Calcium hydroxide content, CH:	The final calcium hydroxide content in the concrete volume (100% cement hydration and pozzolanic action). It has a significant effect on concrete carbonation. UNITS: kg / m^3 of concrete
Calcium-silicate-hydrate content, CSH:	The final calcium-silicate-hydrate content in the concrete volume (100% cement hydration and pozzolanic action). It has a significant effect on concrete strength and concrete carbonation. UNITS: kg / m^3 of concrete
Chemically-bound water content, H:	The final chemically-bound water content in the concrete volume (100% cement hydration and pozzolanic action). UNITS: kg / m^3 of concrete

Minimum water to cement ratio, (W/C)min:	The minimum water/cement ratio required for the completion of clinker hydration and pozzolanic reactions. UNITS: dimensionless (by mass)

and the main volumetric composition of concrete (final):

Concrete porosity, ε:	The ratio of pore volume (final) to the total volume of concrete (100% cement hydration and pozzolanic action). It has a significant effect on concrete strength and concrete durability. UNITS: dimensionless (by volume)
Carbonated-concrete porosity, εc:	The ratio of pore volume (final) to the total volume of the carbonated concrete (100% cement hydration and pozzolanic action- 100% carbonation). It has a significant effect on concrete strength and concrete durability. UNITS: dimensionless (by volume)

By obtaining the above estimation on concrete's chemical and volumetric composition you may:

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

4. STRENGTH APPROXIMATION

4.1 General

In Fig. 4.1.1, the part (tab) of the logical flowchart of EUCON® for a first approximation of the concrete strength is presented. The tab contains:

- a field that the user is mainly informed on the main concrete characteristics that influence its strength and introduces some **input data** regarding efficiency factors of silica fume and/or fly ash, if they added.
- a **calculation button**, and
- a field of the output results presenting the mean compressive strength and the strength class.
- There is also an *optional field* that the user may introduce the compressive strength test results for cement on mortar specimens (according to EN 196-1) that give the strength ratio 2/28 days, and the strength development (with drawing option).

CONCRETE STRENGTH

INPUT

Tab "MIX DESIGN" data

Tab "PHYSICOCHEMICAL CHARACTERISTICS" data

Main concrete characteristics that influence strength (in addition: efficiency factors of additions, silica fume and/or fly ash, if added)

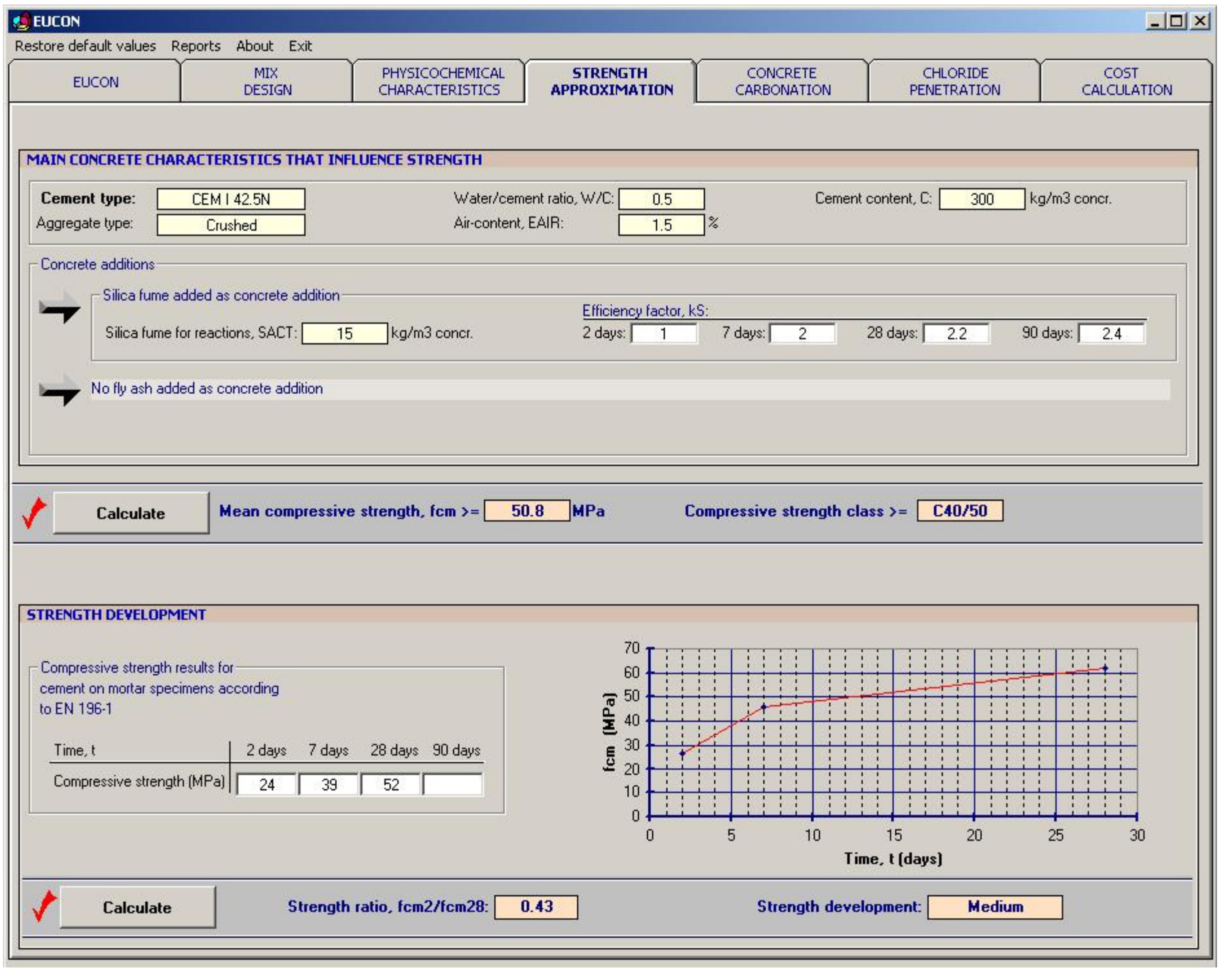
▼

CALCULATION

(Mean compressive strength, strength class, strength ratio 2/28 days, strength development)

Figure 4.1.1 Logical diagram for computer calculation of the concrete strength.

A general view of this tab is given as Fig. 4.1.2. The user has to fill in the “white boxes” or to accept the default values (only in the case when silica fume and/or fly ash are added as concrete additions), and then to press the calculation button in order to have a first approximation of the concrete strength. For the algebraic formulae used for these calculations and further questions, **please always advise the *Theoretical Background* [1], chapter 4**. In the sequence, each part of this tab is discussed in detail.



MAIN CONCRETE CHARACTERISTICS THAT INFLUENCE STRENGTH

Cement type: CEM I 42.5N
Aggregate type: Crushed
Water/cement ratio, W/C: 0.5
Air-content, EAIR: 1.5 %
Cement content, C: 300 kg/m3 concr.

Concrete additions

Silica fume added as concrete addition
Silica fume for reactions, SACT: 15 kg/m3 concr.
Efficiency factor, kS:
2 days: 1
7 days: 2
28 days: 2.2
90 days: 2.4

No fly ash added as concrete addition

Mean compressive strength, fcm >= 50.8 MPa
Compressive strength class >= C40/50

STRENGTH DEVELOPMENT

Compressive strength results for cement on mortar specimens according to EN 196-1

Time, t	2 days	7 days	28 days	90 days
Compressive strength (MPa)	24	39	52	

Strength ratio, fcm2/fcm28: 0.43
Strength development: Medium

Figure 4.1.2 General view of the tab “STRENGTH APPROXIMATION” of the EUCON® program.

4.2 Main concrete characteristics that influence strength

Concrete composition

Cement type:	It is a reminder for the cement type used (see tab "MIX DESIGN").
Water/cement ratio, W/C:	It is a reminder for the water-to-cement ratio used (see tab "MIX DESIGN").
Cement content, C:	It is a reminder for the total cement content in the concrete volume, kg/m^3 (see tab "MIX DESIGN").
Aggregate type:	It is a reminder for the aggregate type used (see tab "MIX DESIGN"). The aggregate type can be crushed or rounded. The rounded aggregates decrease the concrete strength by a factor of 13%, in comparison to the crushed ones [1].
Air content, EAIR:	It is a reminder for the total entrained and entrapped air content in the concrete volume, % (see tab "MIX DESIGN").

Efficiency of additions

Silica fume or fly ash for reactions, SACT or FACT:	It is a reminder of the amount of silica fume or fly ash (when used as concrete additions) that can participate in the pozzolanic reactions (active part), kg/m^3 (see tab "PHYSICOCHEMICAL CHARACTERISTICS").
Efficiency factor of silica fume (kS) or of fly ash (kF):	The efficiency factor (or k-value) is defined as the part of the silica fume or fly ash that can be considered as equivalent to portland cement (CEM I), providing the same concrete properties (obviously k=1 for portland cement). Introduce here the efficiency factors for silica fume (kS) or for fly ash (kF), at the various ages after cast, 2, 7, 28, and 90 days. Use the default values, if you do not have more accurate experimental results. The values at 28 days influence the mean compressive strength. UNITS: dimensionless LIMITS: $0 \leq kS \leq 4$ and $0 \leq kF \leq 2$ DEFAULT VALUE: These in Table 4.2.1

Table 4.2.1 Efficiency factors (k-values) for various supplementary cementing materials (data from [1])*.

Cementitious/ pozzolanic materials	Strength (2 days)	Strength (7 days)	Strength (28 days)	Strength (90 days)
Portland clinker	1	1	1	1
Silica fume	1	2	2.2	2.4
Pozzolana (natural)	0.4	0.3	0.3	0.3
Metakaolin	1	1.8	3	3
Siliceous fly ash	0.2	0.3	0.5	0.7
Calcareous fly ash	1.1	1.1	1.2	1

* All these SCM were ground prior to use up to a fineness of 400±20 m^2/kg according to Blaine's test.

4.3 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 4**. Click on the "**Calculate**" button to estimate:

Mean compressive strength, fcm ≥	The mean compressive strength of concrete should be greater than the estimated value. The estimation is based on the modified Feret's formula (4.3.1) of the reference [1]. UNITS: MPa
Compressive strength class ≥	According to EN 206 [3], the hardened concrete *is classified* with respect to its *compressive strength* according to Table 4.3.1. The characteristic compressive strength at 28 days of 150 mm diameter by 300 mm cylinders ($f_{ck,cyl}$) or the characteristic strength at 28 days of 150 mm cubes ($f_{ck,cube}$) may be used for classification. *Characteristic strength* is the value of strength below which 5% of the population of all possible strength determinations of the volume of concrete under consideration, are expected to fall.

Table 4.3.1 Compressive strength classes for normal-weight and heavy-weight concrete.

Compressive strength class	Minimum characteristic cylinder strength ($f_{ck,cyl}$, MPa)	Minimum characteristic cube strength ($f_{ck,cube}$, MPa)
C8/10	8	10
C12/15	12	15
C16/20	16	20
C20/25	20	25
C25/30	25	30
C30/37	30	37
C35/45	35	45
C40/50	40	50
C45/55	45	55
C50/60	50	60
C55/67	55	67
C60/75	60	75
C70/85	70	85
C80/95	80	95
C90/105	90	105
C100/115	100	115

If the **strength development of the concrete** is required, then the user has to fill in the table at the lower-left corner of the tab with the compressive strength test results for cement on mortar specimens (according to EN 196-1; if available) and then to calculate the strength ratio 2/28 days, and the strength development (with drawing option).

Strength ratio, fcm2/fcm28:	The ratio of the mean compressive strength after 2 days ($f_{cm,2}$) to the mean compressive strength after 28 days ($f_{cm,28}$). UNITS: dimensionless
Strength development:	Information on the *strength development* of the concrete either in terms of Table 4.3.2 or by a strength development curve at 20 ^{o}C between 2 and 90 days.

Table 4.3.2 Strength development of concrete at 20 °C.

Strength development	**Estimate of strength ratio ($f_{cm,2}$ / $f_{cm,28}$)**
Rapid	≥ 0.5
Medium	≥ 0.3 to < 0.5
Slow	≥ 0.15 to < 0.3
Very slow	< 0.15

By obtaining the above estimation for the concrete strength, the user may:

- **accept these results** and continue in the next tabs to estimate service life and 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 general, it has to be emphasized that all the above approach is just *a first rough approximation*, valuable for the initial test proportioning, and a detailed experimental verification is further required.**

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)

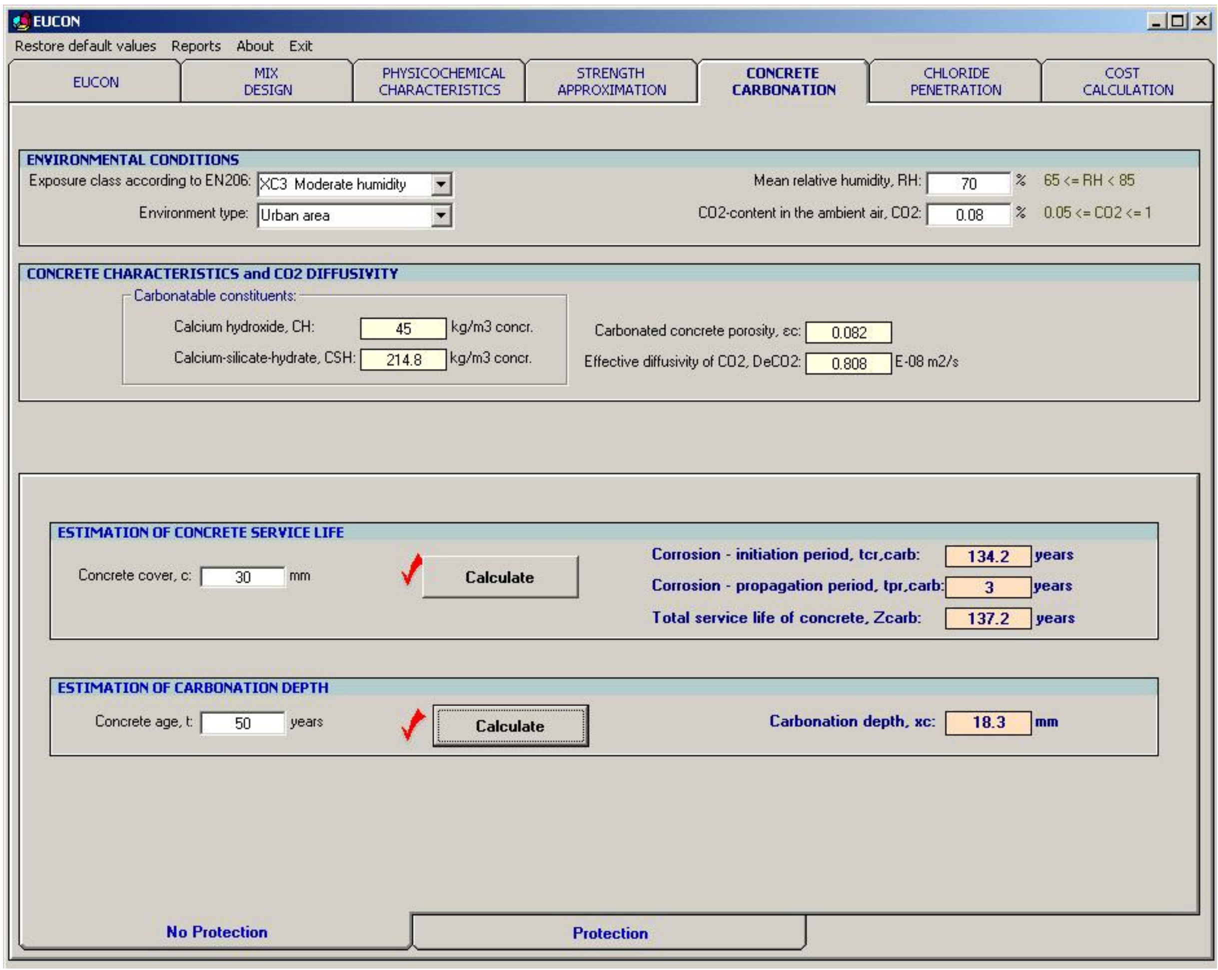
▼

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.



Exposure class according to EN206: XC3 Moderate humidity
Environment type: Urban area
Mean relative humidity, RH: 70 % 65 <= RH < 85
CO2-content in the ambient air, CO2: 0.08 % 0.05 <= CO2 <= 1
Calcium hydroxide, CH: 45 kg/m3 concr.
Calcium-silicate-hydrate, CSH: 214.8 kg/m3 concr.
Carbonated concrete porosity, εc: 0.082
Effective diffusivity of CO2, DeCO2: 0.808 E-08 m2/s
Concrete cover, c: 30 mm
Corrosion - initiation period, tcr,carb: 134.2 years
Corrosion - propagation period, tpr,carb: 3 years
Total service life of concrete, Zcarb: 137.2 years
Concrete age, t: 50 years
Carbonation depth, xc: 18.3 mm

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	$0 \le RH < 45$	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	$45 \le RH < 65$	55
	Permanent wet	Concrete permanently submerged in water	$98 \le RH \le 100$	98
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact, many foundations	$90 \le RH < 98$	90
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity, external concrete sheltered from rain	$65 \le RH < 85$	70
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2	$75 \le RH < 90$	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: $0 \leq c$ 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, L1:	Introduce the total lime content in the mortar volume. UNITS: kg lime / m^3 of mortar LIMITS: $0 \le L1 < DL1$ 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: $0 \le F1 < DF1$ 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: $0 \le S1 < DS1$ 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.

---

*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} ≤ {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 application of mortar coating, ta:	Introduce the time of application of mortar coating after concrete 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.**

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.

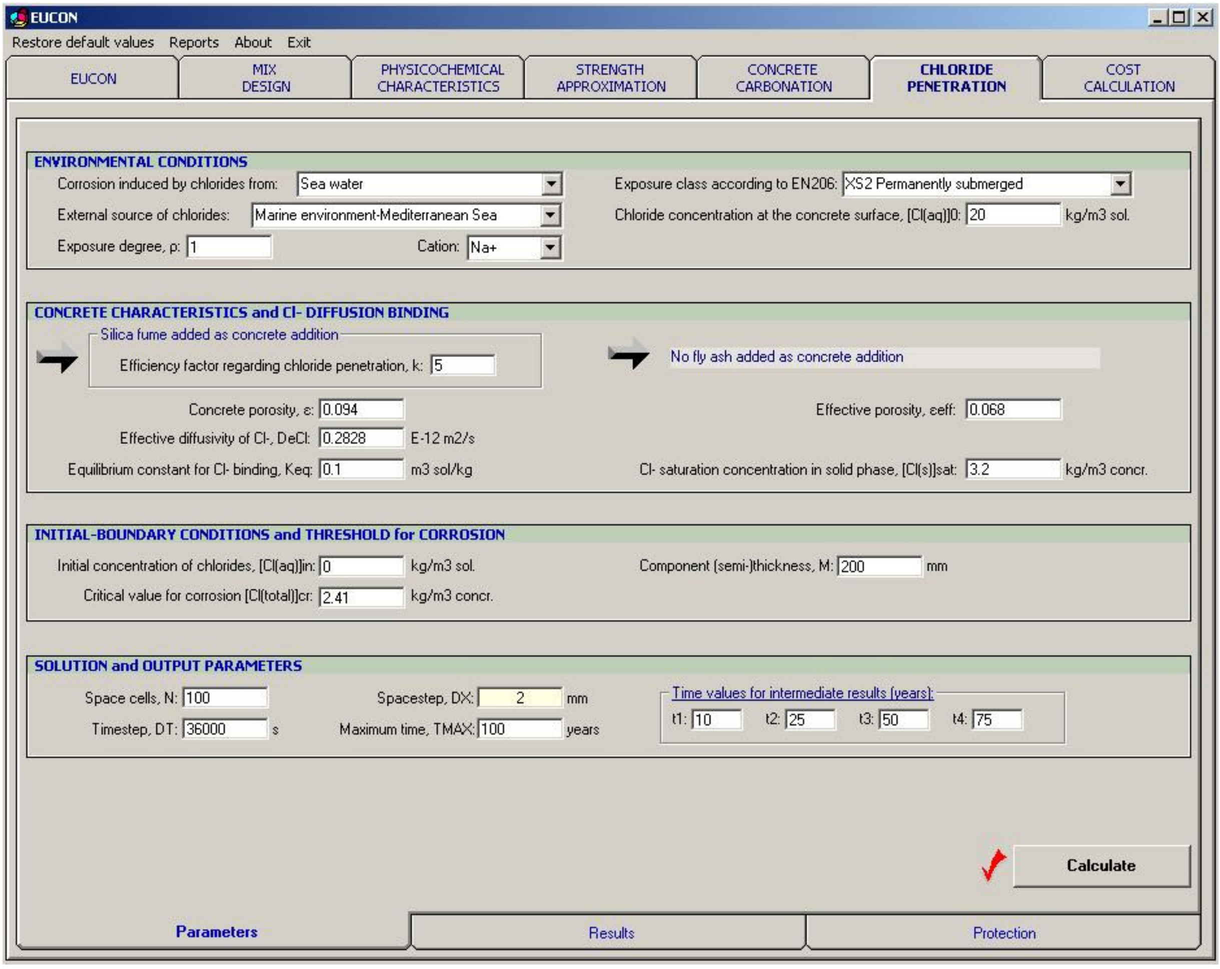
▼

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 degree, ρ:	Introduce the ratio of the exposure time to chlorides to the total time of a complete exposure/non-exposure cycle. The final chloride concentration for estimations will be: $[Cl(aq)]0 = \rho\ [Cl(aq)]0$. 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: $0 < \varepsilon eff < 1$
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.

7. COST CALCULATION

7.1 General

In Fig. 7.1.1, the part (tab) of the logical flowchart of EUCON® is presented for the calculation of the concrete production cost, as well as for the surcharges from the various protection measures against carbonation and chloride ingress. The tab contains:

- a field that the user introduces the **input data** as regards the *purchase cost of constituent materials* for concrete composition.
- a field that the user introduces the **input data** as regards the *other costs for concrete production, transportation and delivery.*
- a field that the user introduces the **input data** as regards the *additional cost of the protection measures,* if any.
- **calculation buttons**, for estimation of the total purchase cost of the constituents and the total concrete production cost.

COST CALCULATION

INPUT

Tab “MIX DESIGN” data

Tab “CONCRETE CARBONATION” data

Tab “CHLORIDE PENETRATION” data

Financial input (purchase cost of constituents, mixing cost, transportation and delivery cost, fixed and other operational costs, cost of the protection measures, if any)

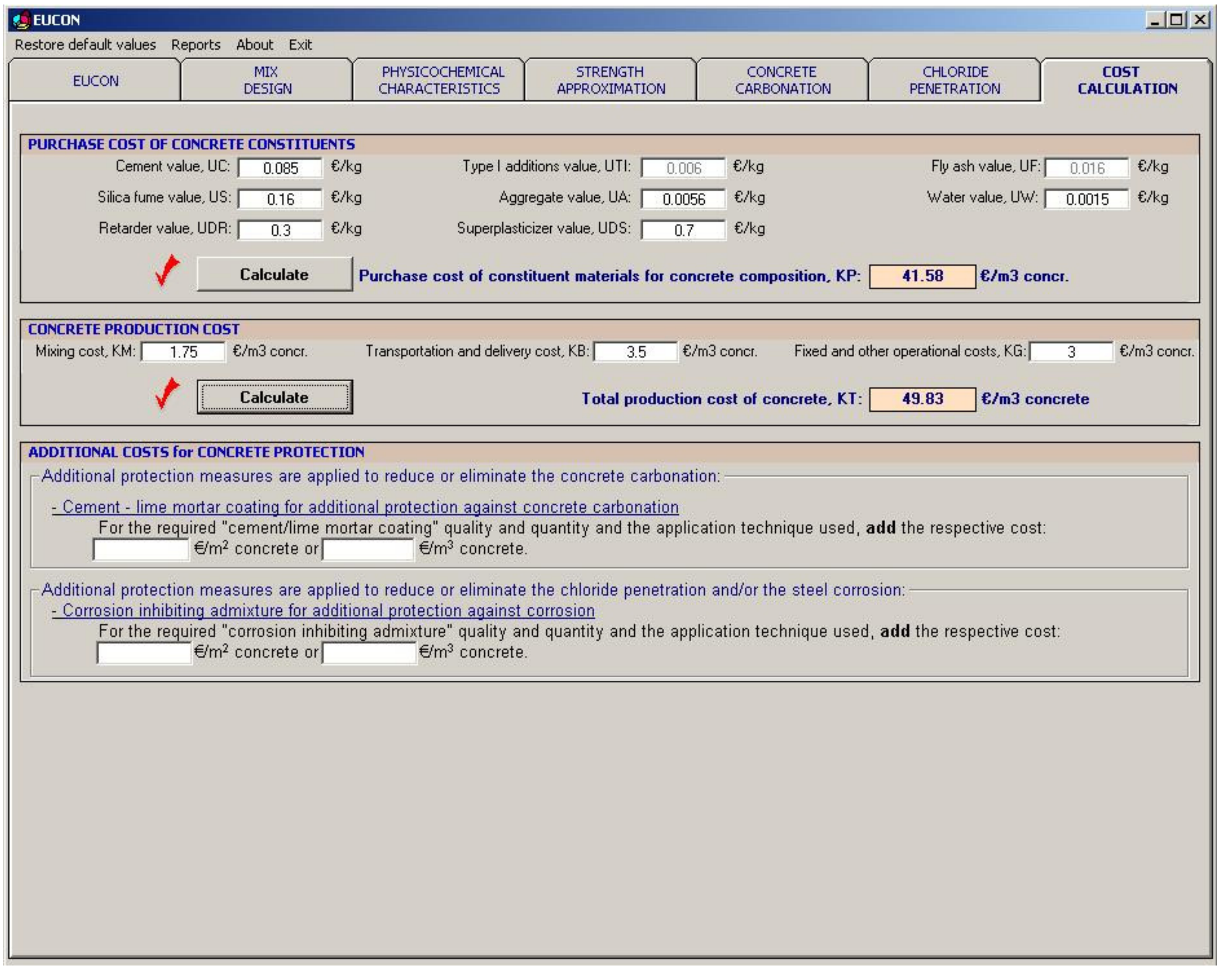
▼

CALCULATION

Total purchase cost of the constituents. Concrete production cost.

Figure 7.1.1 Logical diagram for computer calculation of concrete production cost.

A general view of this tab is given as Fig. 7.1.2. The user has to fill in the “white boxes” or to accept the default values, and then to press the calculation buttons in order to have an estimation of the concrete production cost, as well as of the surcharges from the various protection measures used. For the mathematical formulae used for these calculations and further questions, **please always advise the *Theoretical Background* [1], chapter 7**. In the sequence, each part of this tab is discussed in detail.



PURCHASE COST OF CONCRETE CONSTITUENTS

Cement value, UC: 0.085 €/kg
Type I additions value, UTI: 0.006 €/kg
Fly ash value, UF: 0.016 €/kg
Silica fume value, US: 0.16 €/kg
Aggregate value, UA: 0.0056 €/kg
Water value, UW: 0.0015 €/kg
Retarder value, UDR: 0.3 €/kg
Superplasticizer value, UDS: 0.7 €/kg

Purchase cost of constituent materials for concrete composition, KP: 41.58 €/m3 concr.

CONCRETE PRODUCTION COST

Mixing cost, KM: 1.75 €/m3 concr.
Transportation and delivery cost, KB: 3.5 €/m3 concr.
Fixed and other operational costs, KG: 3 €/m3 concr.

Total production cost of concrete, KT: 49.83 €/m3 concrete

ADDITIONAL COSTS for CONCRETE PROTECTION

Additional protection measures are applied to reduce or eliminate the concrete carbonation:

- Cement - lime mortar coating for additional protection against concrete carbonation

For the required "cement/lime mortar coating" quality and quantity and the application technique used, **add** the respective cost:
€/m² concrete or €/m³ concrete.

Additional protection measures are applied to reduce or eliminate the chloride penetration and/or the steel corrosion:

- Corrosion inhibiting admixture for additional protection against corrosion

For the required "corrosion inhibiting admixture" quality and quantity and the application technique used, **add** the respective cost:
€/m² concrete or €/m³ concrete.

Figure 7.1.2 General view of the tab “COST CALCULATION” of the EUCON® program.

7.2 Purchase cost of concrete constituents

All the following costs represent the value of the concrete constituent materials as they delivered in the ready mix plant or the place where the concrete is manufactured (including transportation to the plant premises).

Cement value, UC:	Introduce the value of cement per weight unit. UNITS: €/kg DEFAULT VALUE: 0.085 €/kg (CEM I)
Type I additions value, UTI:	Introduce the value of Type I additions (filler aggregates and/or pigments), if any, per weight unit. UNITS: €/kg DEFAULT VALUE: 0.006 €/kg (filler aggregate)
Fly ash value, UF:	Introduce the value of fly ash (Type II addition), if any, per weight unit. UNITS: €/kg DEFAULT VALUE: 0.016 €/kg
Silica fume value, US:	Introduce the value of silica fume (Type II addition), if any, per weight unit. UNITS: €/kg DEFAULT VALUE: 0.160 €/kg
Aggregate value, UA:	Introduce the value of aggregates per weight unit. UNITS: €/kg DEFAULT VALUE: 0.0044 €/kg
Water value, UW:	Introduce the value of water per weight unit. UNITS: €/kg DEFAULT VALUE: 0.0015 €/kg
Admixture value, UDi:	Introduce the value of the each specific admixture used, per weight unit of the admixture as delivered. UNITS: €/kg DEFAULT VALUE: 0.30 €/kg (for retarder), 0.75 €/kg (for accelerator), 0.70 €/kg (for air-entraining), 0.42 €/kg (for plasticizer), 0.70 €/kg (for superplasticizer), 1.00 €/kg (for other admixture: corrosion inhibitor)

Click on the "**Calculate**" button to estimate the purchase cost of the constituent materials.

Calculation

Purchase cost of constituent materials for concrete composition, KP:	This cost is estimated from the equation: KP = C.UC + TI.UTI + F.UF + S.US + A.UA + WA.UW + + Σ(UDi . dosage i /100 . C) (The admixture i dosage is the kg admixt./100 kg cement) UNITS: €/m^3 concrete

7.3 Concrete production cost

Mixing cost, KM:	Introduce the cost of material mixing and preparation of the fresh concrete. UNITS: €/m^3 concrete DEFAULT VALUE: 1.75 €/m^3 (includes energy, labour, maintenance)
Transportation and delivery cost, KB:	Introduce the cost of transportation and delivery of the fresh concrete. UNITS: €/m^3 concrete DEFAULT VALUE: 3.50 €/m^3 (includes fuels, labour, maintenance)
Fixed and other operational costs, KG:	Introduce the fixed cost of purchase and establishment of equipment for concrete production, transportation and delivery (depreciation values), other labour and administration costs and general operational costs. UNITS: €/m^3 concrete DEFAULT VALUE: 3.00 €/m^3 (includes fuels, labour, maintenance)

Click on the "**Calculate**" button to estimate the total production cost of concrete.

Calculation

Total production cost of concrete, KT:	This total cost is estimated from the equation: KT = KP + KM + KB + KG UNITS: €/m^3 concrete

7.4 Additional costs for concrete protection

If additional protection measures are applied to reduce or eliminate the **concrete carbonation**, they have to be taken into account in the cost considerations. Two general protection measures may be applied, as given in the “Concrete Carbonation” tab: *waterproof sealants* or *cement – lime mortar coatings*. If they have been used, then the following will appear:

● *Waterproof sealant for additional protection against concrete carbonation*

For the required “waterproof sealant” quality and quantity and the application technique used, **add** the respective cost: _______€/m^2 concrete or _______€/m^3 concrete.

● *Cement – lime mortar coating for additional protection against concrete carbonation*

For the required “cement/lime mortar coating” quality and quantity and the application technique used, **add** the respective cost: _______€/m^2 concrete or _______€/m^3 concrete.

If additional protection measures are applied to reduce or eliminate the **chloride penetration and/or the steel corrosion**, they have to be taken into account in the cost considerations. Several protection measures may be applied, as given in the “Chloride Penetration” tab. If they have been used, then the following will appear:

● *Corrosion inhibiting admixture for additional protection against corrosion*

For the required “corrosion inhibiting admixture” quality and quantity and the application technique used, **add** the respective cost: _______€/m^2 concrete or _______€/m^3 concrete.

● *Corrosion-resistant stainless steel reinforcing bars or epoxy-coated conventional bars*

For the required “specific reinforced bar” quality, **add** the surcharges in cost: _______€/m^3 concrete.

● *Cathodic protection of the reinforcement for additional protection against corrosion*

For the required materials and “cathodic protection” used, **add** the surcharges in cost: _______€/m^3 concrete.

● *Impregnation technique for additional protection against chlorides and corrosion*

For the required materials and "impregnation technique" used, **add** the respective cost: _______€/m^2 concrete or _______€/m^3 concrete.

● *Protective coating for additional protection against chlorides and corrosion*

For the required "protective coating" quality and quantity and the application technique used, **add** the respective cost: _______€/m^2 concrete or _______€/m^3 concrete.

7.5 Final optimization and reporting

By obtaining the above final estimation for the ***concrete production cost and any other additional costs*** as regards concrete protection against carbonation, chlorides and corrosion, you may:

- **accept the cost results, as well as and the previous strength and durability results,** and terminate the design procedure.
- Otherwise, **you may change any input data mainly from the tab "MIX DESIGN"** or other tabs where specific protection measures are proposed, in order to correct the output results of this tab, **until final acceptance.**

By using the separate actions such as **Reports** or **Exit**, the user may create a report file or, finally, exit.

Notation

Latin Letters

A	aggregate-content in concrete volume (kg/m^3)
A/C	aggregate-to-cement ratio, by weight
c	concrete cover: distance of reinforcement from the outer surface of concrete (mm)
C	initial cement-content in concrete volume (kg/m^3)
CH	calcium hydroxide content in concrete volume (kg/m^3)
$[Cl^-(aq)]$	concentration of Cl^- in the aqueous phase of concrete (kg/m^3 pore solution)
[Cl(aq)]0	concentration of Cl^- at the concrete surface (kg/m^3 aqueous solution)
[Cl(aq)]in	initial (at t=0) concentration of Cl^- (kg/m^3 aqueous solution)
$[Cl^-(s)]$	concentration of Cl^- in the solid phase of concrete (kg/m^3 concrete)
[Cl(s)]sat	saturation concentration of Cl^- in the solid phase (kg/m^3 concrete)
[Cl(tot)]cr	critical total concentration of Cl^- for steel corrosion (kg/m^3 concrete)
CO2	carbon dioxide content in the ambient air at the concrete surface (%)
CS	calcium sulphate content in concrete (kg/m^3 of concrete)
CSH	calcium silicate hydrate content in concrete volume (kg/m^3)
d	thickness of mortar coating (mm)
D	total admixture-content (solids) in concrete volume (kg/m^3)
DA	aggregate density (kg/m^3)
DC	cement density (kg/m^3)
DCON	fresh concrete density (kg/m^3)
DD	admixture (solids) density (kg/m^3)
DeCl	intrinsic effective diffusivity of Cl^- in concrete (m^2/s)
DeCO2	effective diffusivity of CO_2 in carbonated concrete (m^2/s)
DF	fly ash density (kg/m^3)
DL	lime density (kg/m^3)
DMAX	maximum nominal upper aggregate size (mm)
DS	silica fume density (kg/m^3)
DT	the timestep in the numerical solution (s)

DTI	Type I addition’s density (kg/m^3)
DTOT	total admixture-content (solids and water, as supplied) in concrete volume (kg/m^3)
DW	water density (kg/m^3)
DX	the spacestep in the numerical solution, M/N (mm)
EAIR	volume of entrained or entrapped air per concrete volume (%, m^3/m^3)
ENT	volume of entrained air per concrete volume (%, m^3/m^3)
ETR	volume of entrapped air per concrete volume (%, m^3/m^3)
$f_{ck,cube}$	characteristic compressive strength of concrete determined by testing cubes (MPa)
$f_{ck,cyl}$	characteristic compressive strength of concrete determined by testing cylinders (MPa)
fcm	mean compressive strength of concrete (at 28 days, MPa)
fcm2	mean compressive strength of concrete at 2 days (MPa)
fcm28	mean compressive strength of concrete at 28 days(MPa)
F	fly ash content in concrete volume (kg/m^3)
FACT	maximum part of fly ash that may participate in the pozzolanic reactions
H	chemically-bound water content in concrete volume (kg/m^3)
k	efficiency factor of SCM comparing to portland cement
kF	efficiency factor of fly ash comparing to portland cement
kS	efficiency factor of silica fume comparing to portland cement
K	clinker content in concrete (kg/m^3 of concrete)
KT	total production cost of concrete (CU/m^3)
KB	cost of concrete transportation and delivery (CU/m^3)
Keq	equilibrium constant for Cl^- binding (m^3 of pore solution/kg)
KG	fixed and general costs in concrete production (CU/m^3)
KM	mixing cost for concrete production (CU/m^3)
KP	purchase cost of materials for concrete production (CU/m^3)
L	lime content in mortar volume (kg/m^3)
L/C	lime-to-cement ratio, by weight
M	distance between outer surface and axis of symmetry (mm)
MAC	mac content in concrete (kg/m^3 of concrete)
N	the number of cells that the distance M is separated for the numerical solution
PCS	percentage of calcium sulphate in the cement (%)
PK	percentage of clinker in the cement (minus calcium sulphate) (%)
PL	the percentage of the pure CH in the lime

PMAC	percentage of minor additional const. in the cement (minus calcium sulphate) (%)
PPO	percentage of other pozzol. materials in the cement CEM V (minus calc. sulph.) (%)
PSCM	percentage of SCM in the cement (minus calcium sulphate) (%)
PSL	percentage of slag in the cement CEM V (minus calcium sulphate) (%)
P	SCM content in concrete (kg/m^3 of concrete)
r	degree of pozzolanic reaction of a cement SCM or a concrete addition
RH	ambient relative humidity (%)
S	silica fume content in concrete volume (kg/m^3)
SACT	maximum part of silica fume that may participate in the pozzolanic reactions
SL	slag content in concrete (kg/m^3 of concrete)
t	time (years)
ta	time of application of mortar coating (years)
tcr,carb	critical time required for reinforcement depassivation due to carbonation (years)
tcr,chlor	critical time required for reinforcement depassivation due to chlorides (years)
td	time required for total carbonation of mortar coating (years)
tpr,carb	critical time required for carbonation-induced corrosion to split the cover (years)
TMAX	the maximum time that the numerical solution terminates (years)
TI	Type I addition content in concrete volume (kg/m^3)
U…	value of concrete constituent C, TI, F, S, A, W, or D, per unit (€/kg)
W	initial water-content (effective) in concrete volume (kg/m^3)
WA	water added in concrete volume (kg/m^3)
WD	water added from admixtures in concrete volume (kg/m^3)
W/C	water-to-cement ratio, by weight
x	distance from the outer surface of concrete (m)
xc	concrete carbonation depth measured from concrete surface (mm)
xca	intitial (without any coating) carbonation depth of concrete (mm)
Zcarb	designed service life of a concrete structure regarding carbonation (years)
…1	quantities reffering in cement-lime mortar coatings

Greek Letters

γA	weight fraction of Al_2O_3, which contributes to the pozzolanic reactions (%)
γS	weight fraction of SiO_2, which contributes to the pozzolanic reactions (%)

ε	total concrete porosity (m^3 pore volume /m^3 concrete)
εc	porosity of carbonated concrete
εeff	effective porosity of concrete regarding chloride diffusion
ρ	ratio of the exposure time to the total time of a complete cycle

Abbreviations

AASHTO	American Association of States Highway and Transportation Officials
ACI	American Concrete Institute
AFM	atomic force microscopy
ASTM	American Society for Testing and Materials
BET	Brunauer, Emmett and Teller (method of)
CCP	concrete compositional parameters
C…/…	compressive strength classes in case of normal-weight and heavy-weight concrete
CAL	calcareous
CEB	Comité Euro-international du Béton
CEM…	cement type according to the series EN 197
CEN	Comité Européen de Normalisation
CH	calcium hydroxide
CSH	calcium silicate hydrate
EN	European Standard
mac	minor additional constituent
OPC	ordinary (normal) portland cement
RH	relative humidity
RILEM	Réunion Intern. des Laborat. d'Essais et de Recherches sur les Mat. et les Constr.
SCM	supplementary cementing materials
SEM	scanning electron microscopy
SIL	siliceous
X0	exposure class for no risk of corrosion or attack
XC…	exposure classes for risk of corrosion induced by carbonation
XD…	exposure classes for risk of corrosion induced by chlorides other than from sea water

XS…	exposure classes for risk of corrosion induced by chlorides from sea water
XF…	exposure classes for freeze/thaw attack
XA…	exposure classes chemical attack

Cement Technology Notation

S: SiO_2

A: Al_2O_3

F: Fe_2O_3

C: CaO

M: MgO

H: H_2O

$\bar{S}$: SO_3

$\bar{C}$: CO_2

LOI: loss on ignition

References

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