Development of a Software Package based on Proven Predictive Models for the Estimation of Concrete Service Life

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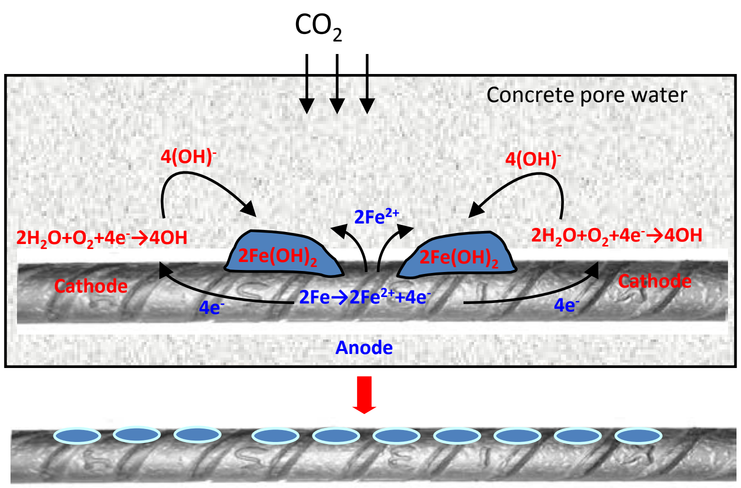
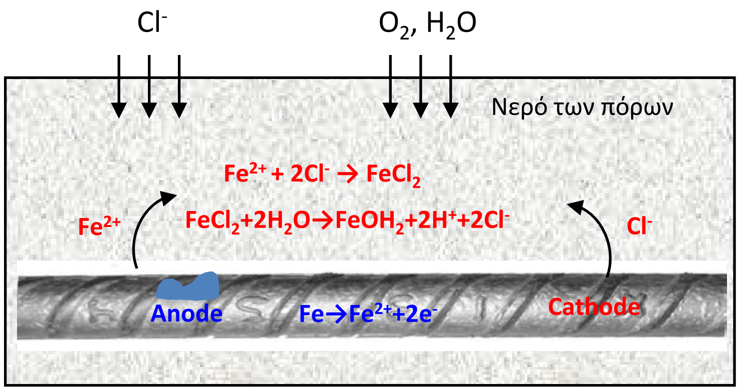
Introduction

- **Premature Structural Deterioration is a major concern**
  - Observed deterioration: combination of mechanical and environmental effects
  - Corrosion of steel reinforcement most serious outcome of these actions (carbonation, chloride ingress)





- **Emphasis should be given on:**
  - understanding and modeling deterioration mechanisms and physicochemical processes
  - Developing service life estimation models

Introduction

- **On EN 206-1 durability is approached by:**
  - Definition of limiting parameters on cement/concrete composition
  - Development of performance related methods (based on proven predictive models).

- **A performance-related method considers:**
  - *deterioration mechanisms*
  - *service life* of element or structure
  - *criteria* which define end of service life (in a quantitative way)

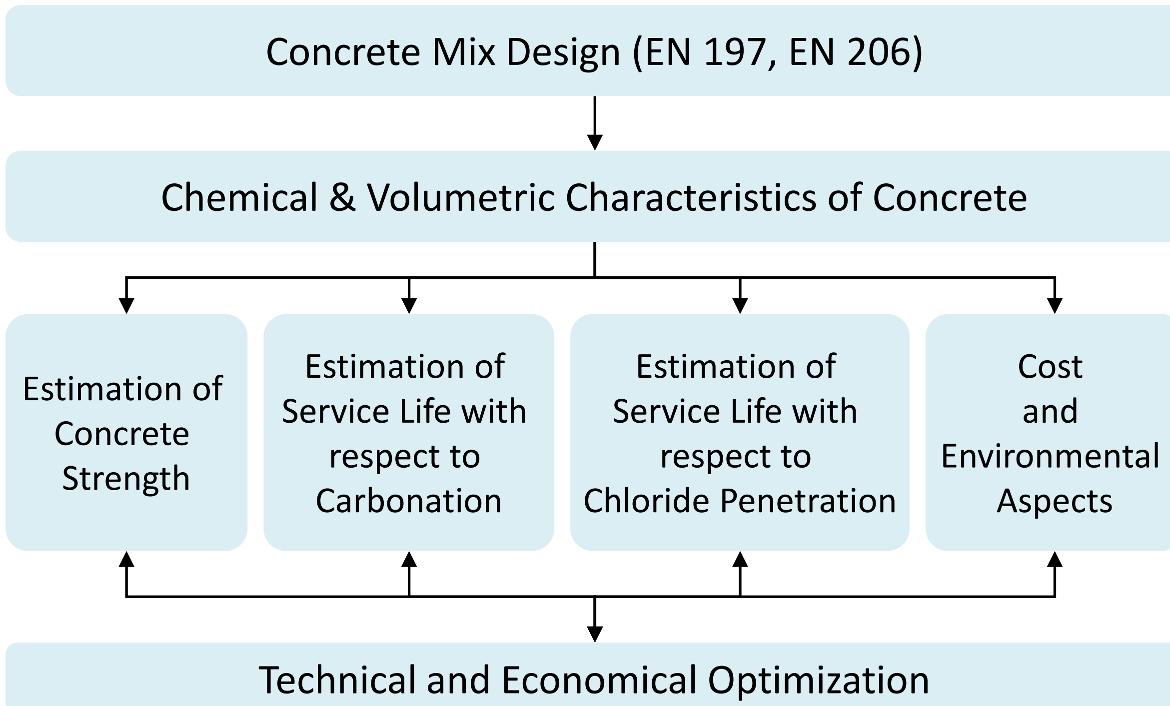
- **It may be based:**
  - on satisfactory experience with local practices in local environments
  - on data from an established performance test method
  - on the use of proven predictive models

- ***Development of Simulation tool based on proven predictive models according to performance related methods is a necessity***

Simulation Tool - Principles

- Initial approach of **concrete composition** in order to satisfy structural requirements
- Calculation of main **chemical and volumetric characteristics of concrete** (chemical composition of hydrated cementitious materials, porosity, reaction degree of SCM etc.)
- Estimation of concrete **compressive strength class**
- Definition of the **environmental conditions** where the structure will be exposed
- Utilisation of **appropriate proven predictive model**, for each significant deterioration mechanism, according to the specific environment where the structure would be found
- Estimation of structure **service life** and improvement of the initial mix design, if required
- **Technical and economical optimization.**

Simulation Tool - Schematic



Simulation Tool - Schematic

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CONCRETE MIX DESIGN (according to EN 197, EN 206)		
INPUT	Cement Type	Selection of 27 cement types (ENV-197), Standard Cement Strength Class. Composition in clinker, other main constituents, minor constituents, gypsum. Cement density and content
	Additions	Type I (filler aggregate and/or pigments), Type II (siliceous/calcareous fly ash, silica fume), additions density and content
	Admixtures	(Retarder, accelerator, air-entraining, plasticizer, superplasticizer), density, solid content, dosage. Total admixture content
	Water	Water added, water from admixtures and aggregates, water density and content
	Aggregates	Aggregate type, aggregate density, maximum nominal aggregate size
	Air	Entrapped-air content, entrained-air content, total air content
OUTPUT	Aggregate content, fresh concrete density	

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CHEMICAL & VOLUMETRIC CHARACTERISTICS OF CONCRETE	
INPUT	Cement Composition, Oxide Analysis and activity
OUTPUT	Reaction degree of other main constituents of cement and concrete additions. Calcium hydroxide, calcium silicate hydrate, chemically-bound water contents, porosity

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ESTIMATION OF CONCRETE STRENGTH	ESTIMATION OF SERVICE LIFE WITH RESPECT TO CARBONATION	ESTIMATION OF SERVICE LIFE WITH RESPECT TO CHLORIDE PENETRATION	COST & ENVIRONMENTAL ASPECTS
INPUT	INPUT	INPUT	INPUT
All of the previous	All of the previous, plus environmental conditions • Exposure class • Relative Humidity, • CO_2-content in air	All of the previous, plus environmental conditions • Exposure class • Relative Humidity • CO_2-content in air	All of the previous, plus • Financial input (purchase cost of materials, mixing, transport, delivery cost) • Environ. Input (environmental impact from materials production)
OUTPUT	OUTPUT	OUTPUT	OUTPUT
• Mean compressive strength • Strength Class • Strength ratio 2/28 days • Strength Development	• corrosion-initiation period, propagation period, • total service life (for specific concrete cover)	• Adequate concrete cover needed to sustain a corrosion free structure, for a given service life • corrosion-initiation period	• Concrete production cost • Environmental cost

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TECHNICAL AND ECONOMICAL OPTIMIZATION
Mixture proportions optimization to achieve the specified strength and durability at the lowest cost.

Simulation Tool : EUCON

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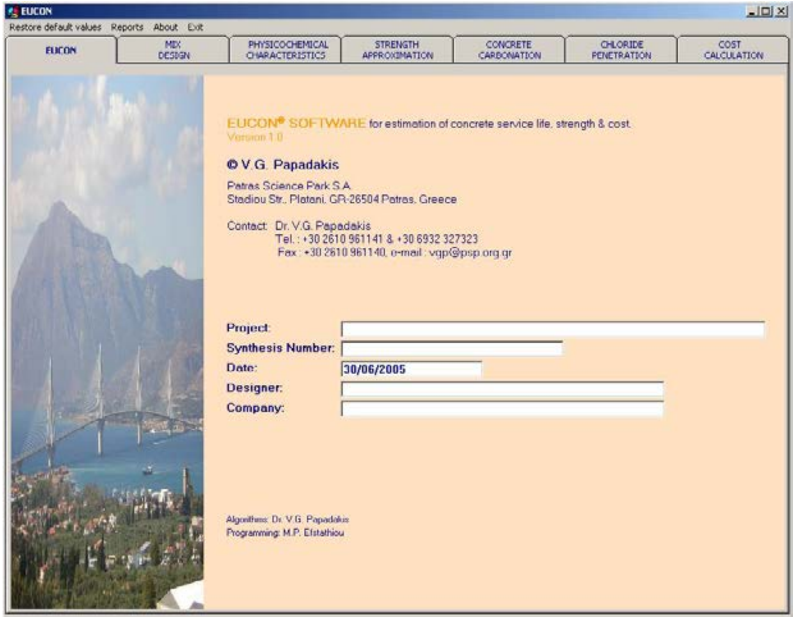

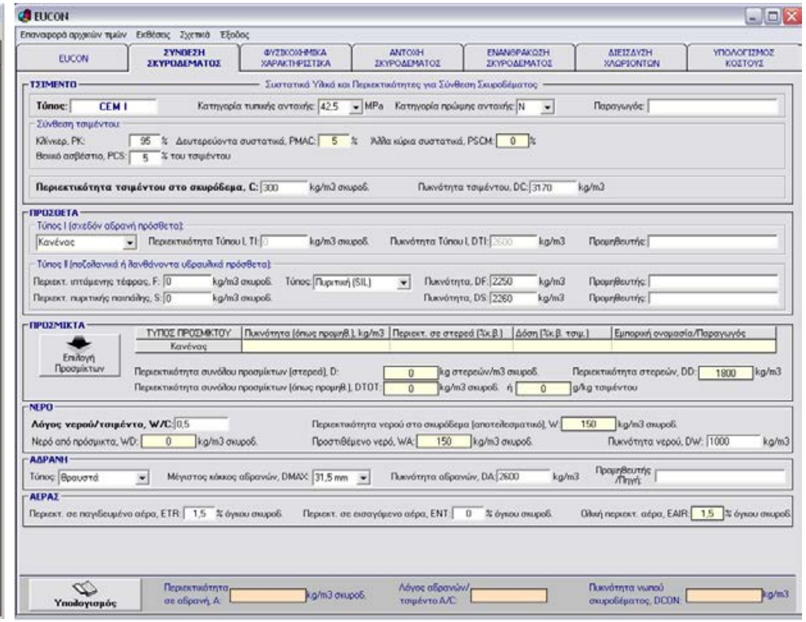

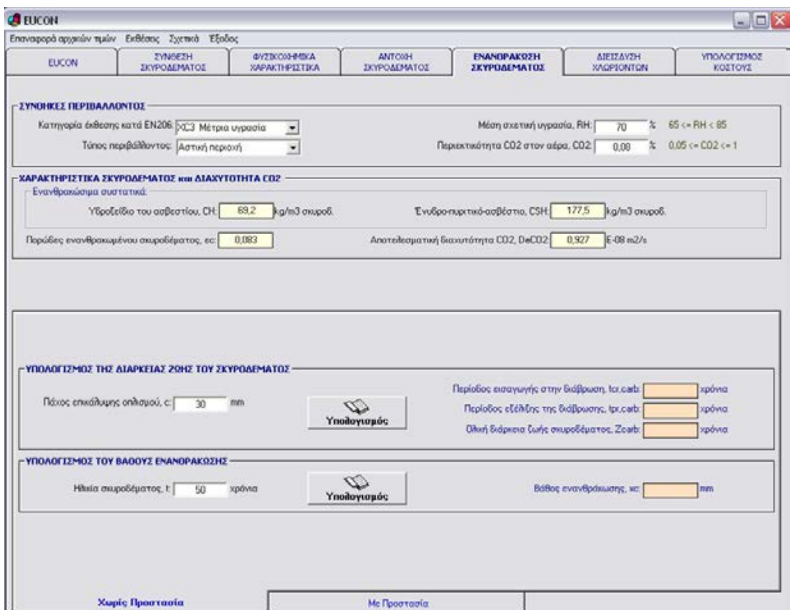

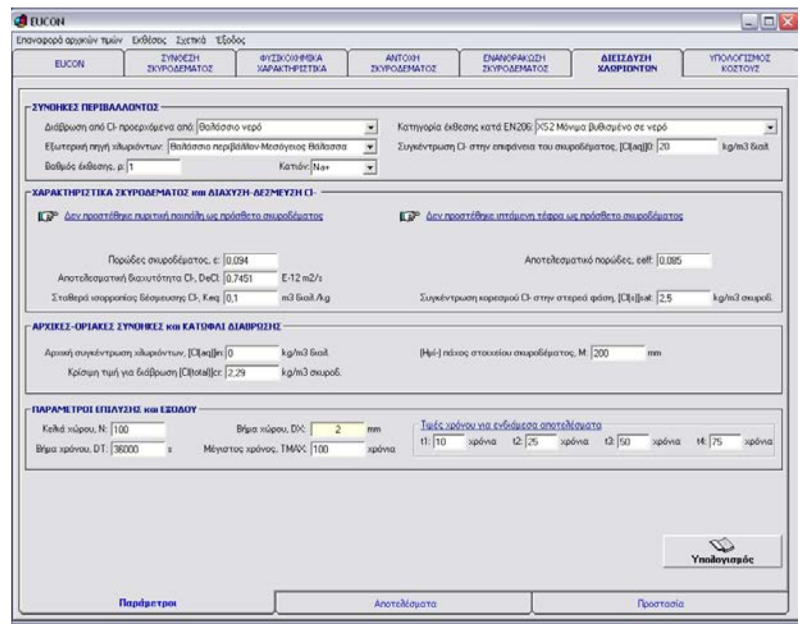

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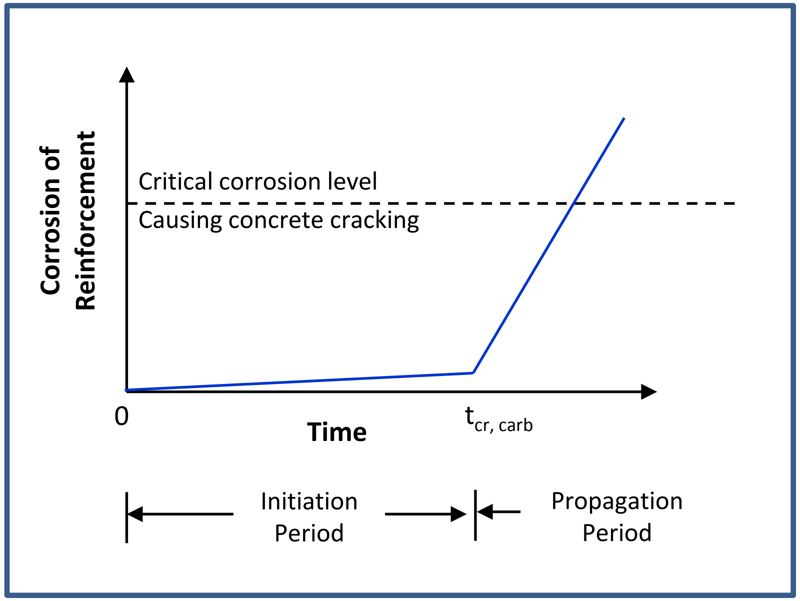
- **Estimation of carbonation depth (x_C) and of critical time for corrosion initiation ($t_{cr, carb}$)**

$$x_C = \sqrt{\frac{2 D_{e,CO2}\left(\frac{CO_2}{}\right) t}{0.33CH + 0.214CSH}}$$

$$t_{cr,carb} = \frac{(0.33CH + 0.214CSH)c^2}{2 D_{e,CO2}\left(\frac{CO_2}{100}\right)}$$



CO_2: CO_2 content in ambient air at the concrete surface (%)

CH, CSH: Contents of $Ca(OH)_2$ and C-S-H in concrete (kg/m^3)

$D_{e,CO2}$: Effective diffusivity of CO_2 in carbonated concrete (m^2/s)

$$D_{e,CO2} = 6.1 \cdot 10^{-6} \cdot \left(\frac{\varepsilon_c - \varepsilon_{air}}{1 - \frac{A}{d_A}}\right)^3 \cdot (1 - RH/100)^{2.2}$$

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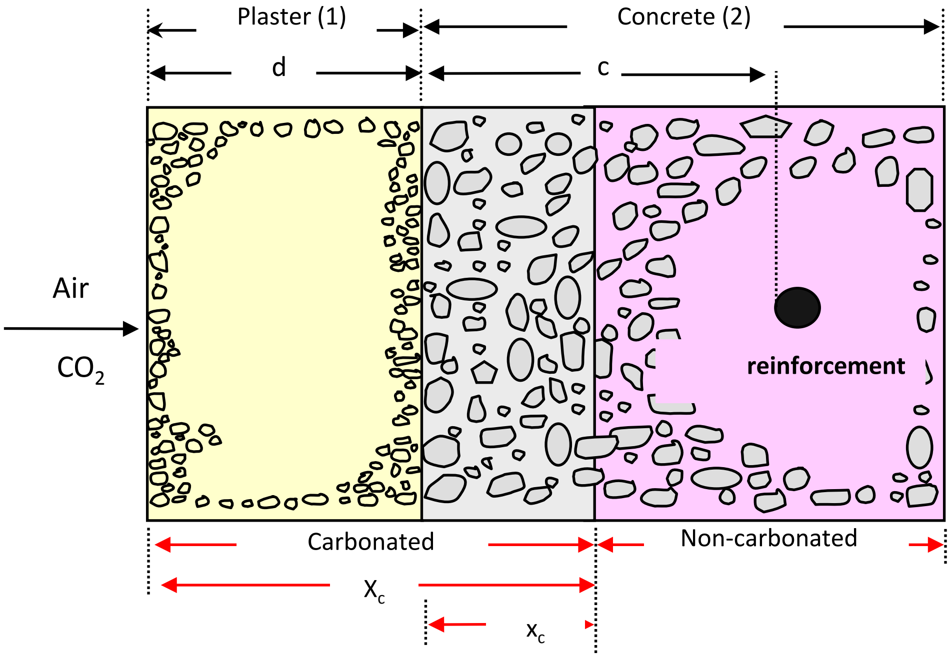
- **Estimation of critical time for corrosion initiation ($t_{cr, carb}$) when protective mortar coating is applied**

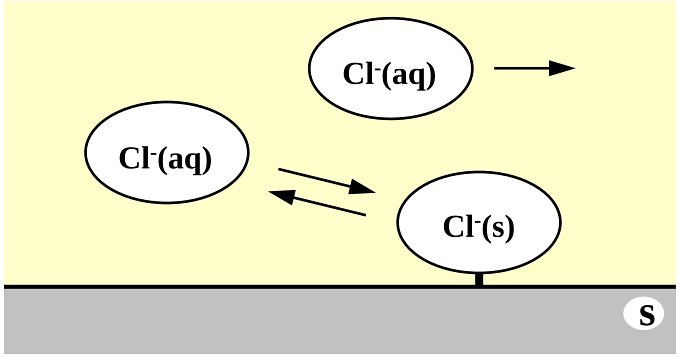


$$t_{cr,\,carb} = t_d + \frac{(0.33CH^{(2)} + 0.214CSH^{(2)})(c^2 + 2dcD^{(2)}_{e,CO2} / D^{(1)}_{e,CO2})}{2D^{(2)}_{e,CO2}(CO_2/100)}$$

Estimation of Service Life for Chloride Exposure

- **Non-linear partial differential equation describing the physicochemical processes of Cl^- diffusion in aqueous phase, adsorption and binding in solid phase of concrete, and desorption.**

$$\frac{\partial [Cl(aq)]}{\partial t} = \frac{D_{e,Cl}\left(1+K_{eq}[Cl(aq)]\right)^2}{K_{eq}[Cl(s)]_{sat} + \varepsilon\left(1+K_{eq}[Cl(aq)]\right)^2}\frac{\partial^2 [Cl(aq)]}{\partial x^2}$$



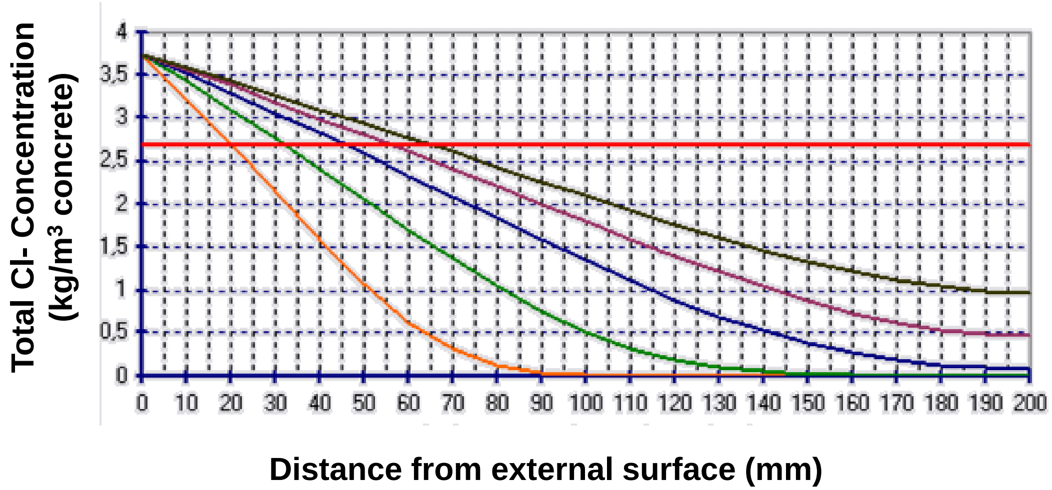
$$[Cl(s)] = \frac{K_{eq}[Cl(aq)]}{1+K_{eq}[Cl(aq)]}[Cl(s)]_{sat}$$

$$D_{e,Cl^-} = \frac{2.4\cdot 10^{-10}}{\left(\frac{K+CS+\sum(kP_{ACT})}{d_c}+\frac{W}{d_w}\right)^2}\cdot\left(\varepsilon_{eff}\right)^{3.5}$$

[Cl(aq)] : concentration of Cl^- in the aqueous phase (kg/m^3)
[Cl(s)] : concentration of Cl^- bound in the solid phase (kg/m^3)
X : distance from the concrete surface (m), t: χρόνος (s)
$D_{e,Cl-}$: intrinsic effective diffusivity of Cl^- in concrete (m^2/s)
K_{eq} : equilibrium constant for Cl^- binding (m^3 of pore volume/kg)
$[Cl(s)]_{sat}$: saturation concentration of Cl^- in the solid phase (kg/m^3 concrete)

Estimation of Service Life for Chloride Exposure

- **Calculation of total Cl^- concentration and of Cl^- concentration bound in the solid phase and aqueous phases , as a function of the initial Cl^- surface concentration and the distance from the surface of the concrete element.**



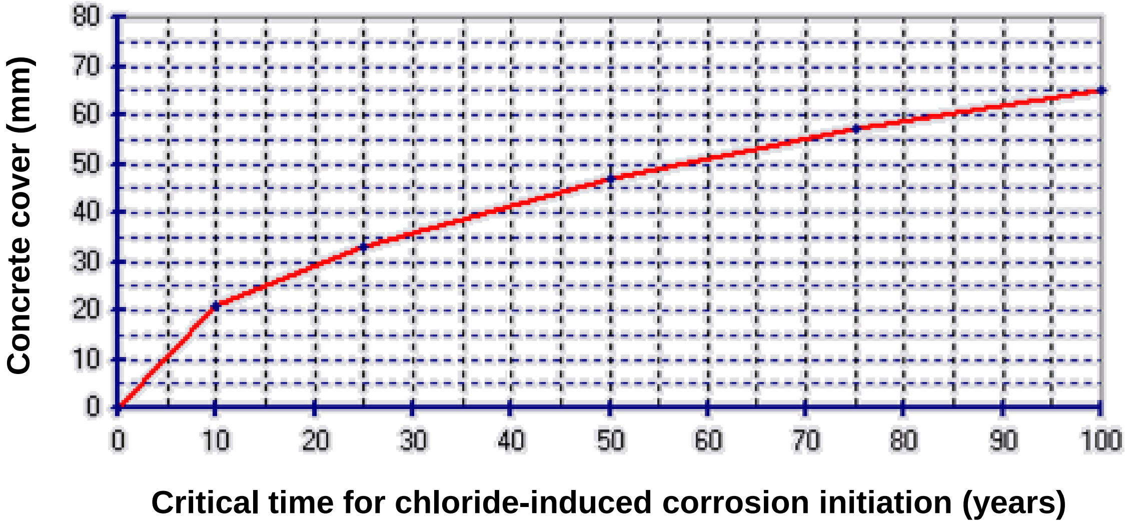
-- 10 years – 25 years – 50 years – 75 years – 100 years – corrosion initiation

Distance from surface (mm)	Cl^- concentration in pore water (kg/m^3 solution)	Cl^- concentration in solid phase (kg/m^3 concrete)	Total Cl^- concentration (kg/m^3 concrete)
0	20	1,667	3,547
10	16,725	1,565	3,137
20	13,539	1,438	2,711
30	10,537	1,283	2,273
40	7,817	1,097	1,832
50	5,469	0,884	1,398
60	3,569	0,658	0,993
70	2,151	0,443	0,645
80	1,19	0,266	0,378
90	0,605	0,143	0,199
100	0,283	0,069	0,095

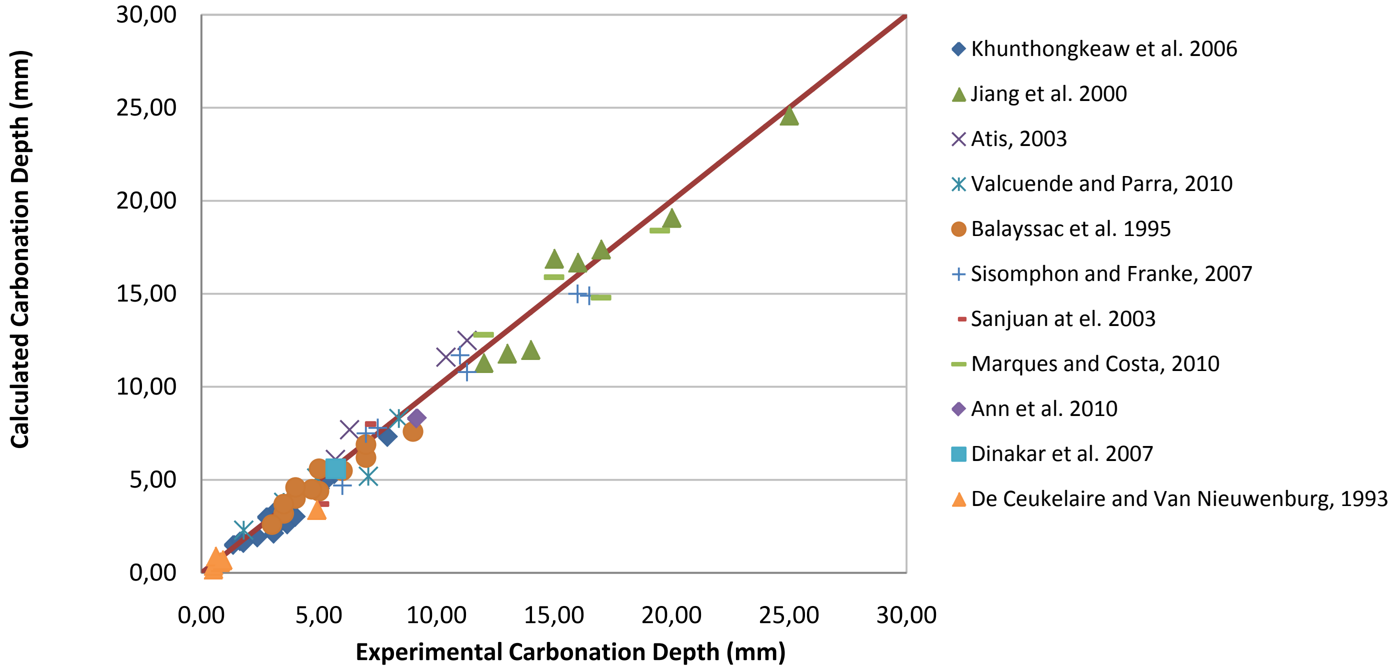
- estimation of the **critical time for chloride-induced corrosion** required for the total chloride concentration surrounding the reinforcement (located at a distance c from surface) to increase over the threshold for depassivation,

- calculation of the **adequate (minimum) concrete cover** needed in order to sustain a chloride-induced corrosion free structure for a given service life

$$t_{cr,Cl^-} = \frac{[Cl^-(s)]_{sat} \cdot c^2}{2 \cdot D_{e,Cl^-} \cdot \left[Cl^-(aq)\right]_0 \cdot \left(1 - \frac{\left[Cl^-(aq)\right]_{cr}}{\left[Cl^-(aq)\right]_0}\right)^2}$$

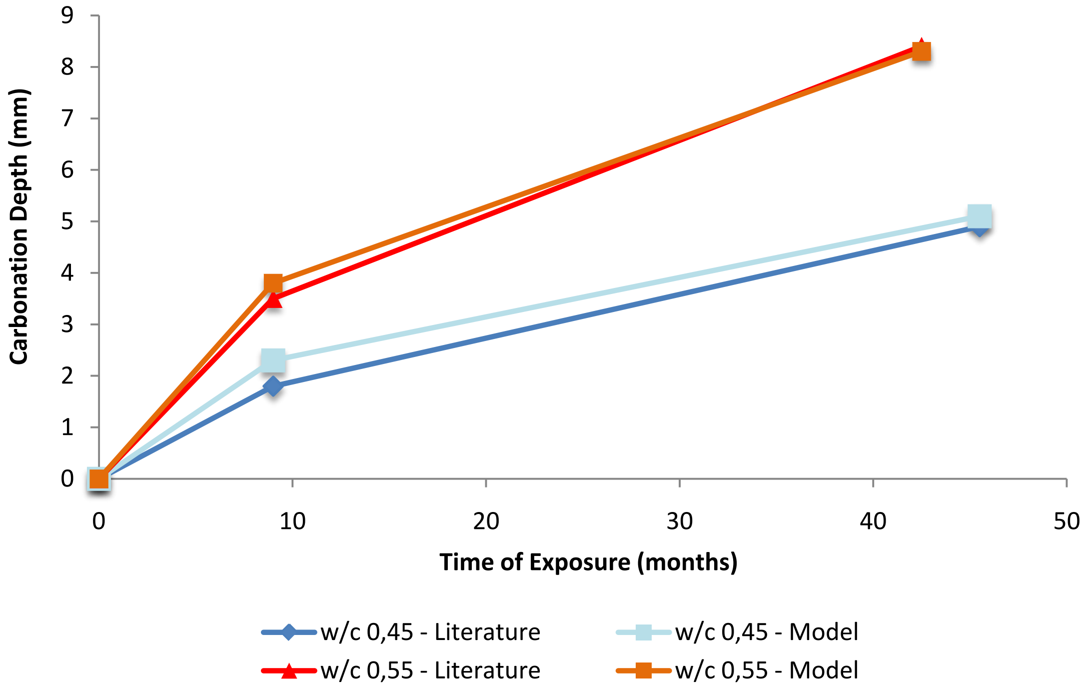


Verification of service life for carbonation (literature)



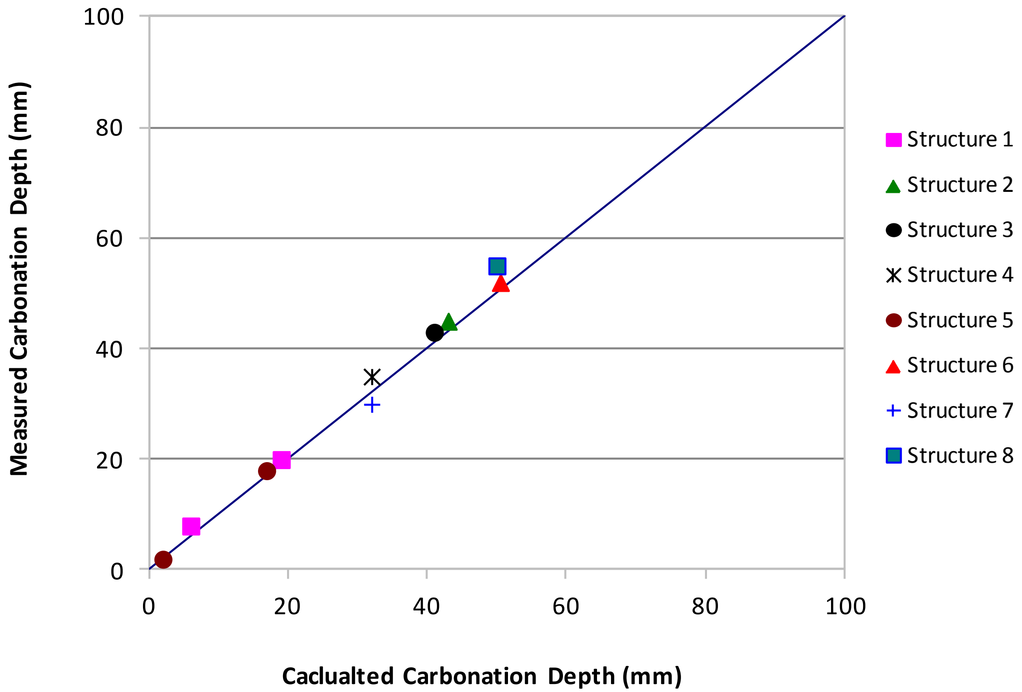
Reference	Cement type	w/c	RH (%)	CO_2 (%)	Exp. X_c (mm)	Calc. X_c (mm)	Exposure Time
Khunthongkeeaw et al. 2006	CEM I	0.67	72.5	0.0625	5.68	5.30	2 year
Sisomphon & Franke 2007	CEM I + fa	0.68	65.0	3	7.50	7.80	4 weeks *
Sisomphon & Franke 2007	CEM I + fa	0.68	65.0	3	11.0	11.7	9 weeks *
Ann et al. 2010	CEM I	0.45	60.0	0.08	11.62 (2.45)	8.30	18 years
Valcuende & Parra, 2010	CEM II/B-M	0.55	60.8	0.035	3.50	3.80	9 months
Valcuende & Parra, 2010	CEM II/B-M	0.55	60.8	0.035	8.40	8.30	42.5 months
Balayassac et al. 1995	CEM II/B-L	0.48	60.8	0.035	3.00	2.60	6 months
Balayassac et al. 1995	CEM II/B-L	0.48	60.8	0.035	3.50	3.70	12 months
Balayassac et al. 1995	CEM II/B-L	0.48	60.8	0.035	4.00	4.60	18 months
Marques and Costa, 2010	CEM II/A-L	0.60	65.0	5	15.0	15.9	42 days *
Dinakar et al. 2007	CEM II/A-V	0.54	65.0	5.0	5.71	5.6	1 year *
Sisomphon, 2007	CEM III/B	0.60	65.0	3	16.00	15.0	9 weeks *
Marques and Costa, 2010	CEM IV/B	0.55	65.0	5	19.50	18.4	42 days *

Verification of service life for carbonation (literature)



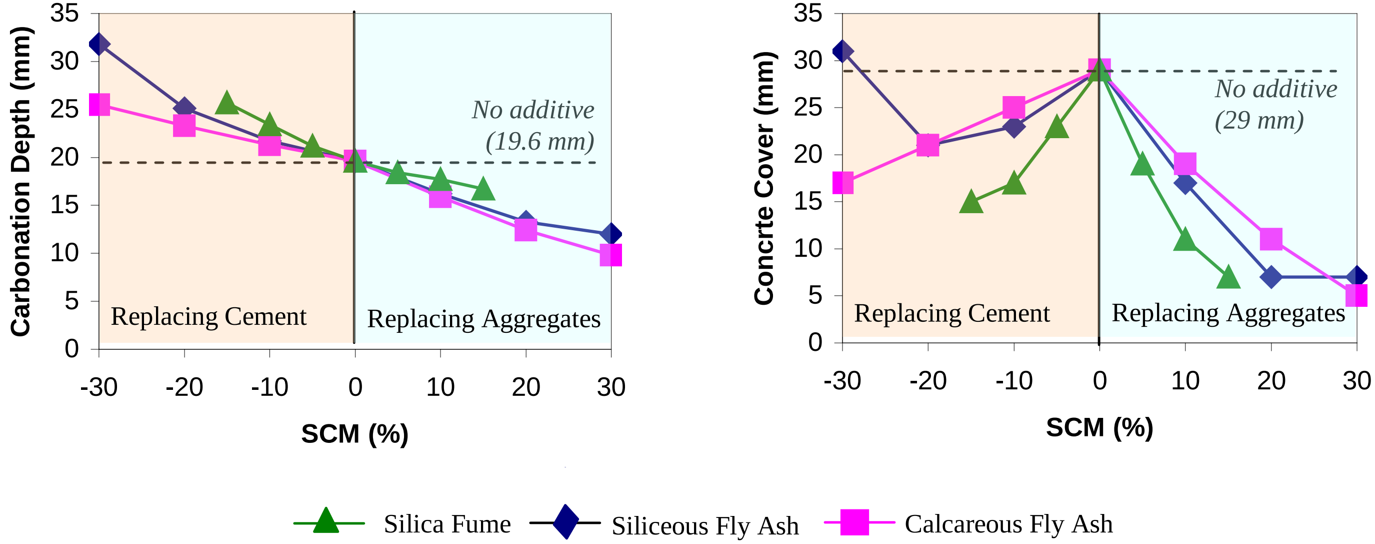
Calculated and experimental carbonation depth values for different w/c ratios of a CEM II/B-M type of cement

Verification of service life for carbonation (field data)



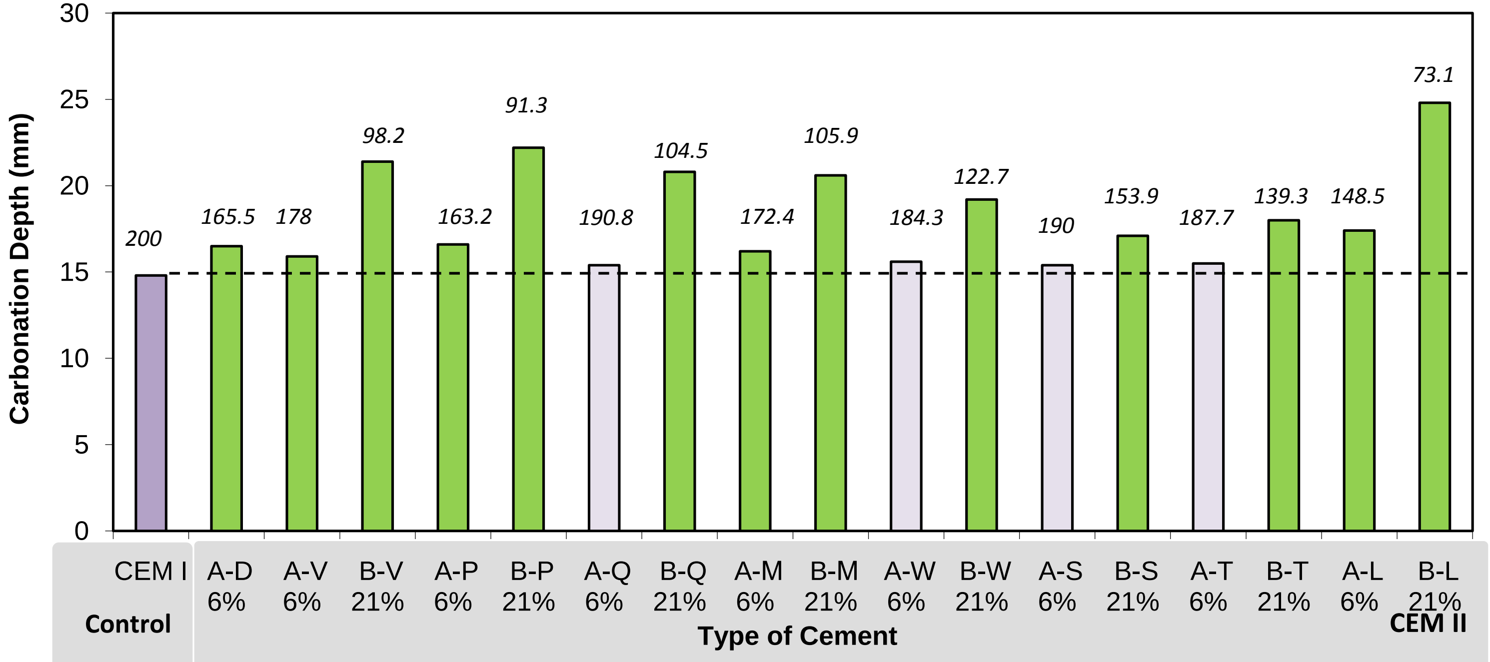
Structure		Age (years)	Carbonation Depth (mm)	
			Measured	Calculated
1	Industrial facility, (mortar coating)	70	8	6
1	Industrial facility, (no mortar coating)	70	20	19
2	School, Mesologi, Greece	66	45	43
3	Hospital, Lixouri, Greece	51	43	41
4	Town Hall,	38	35	32
5	Cooling Tower, (internal)	25	2	2
5	Cooling Tower, (external)	25	18	16.9
6	School,	30	52	50.5
7	Hotel,	37	30	32
8	City Hall,	40	55	50

Utilisation – Effect of Type II additives on service life



- Incorporation of calcareous fly ash (C-FA) in CEM I type of cement, produced a better performance for carbonation exposure than siliceous fly ash (S-FA)
- Specimens incorporating an SCM, whether it substitutes aggregate or cement, exhibit significantly lower total chloride content for all depths from the surface

Utilisation– Effect of CEM II cements on service life (carbonation)



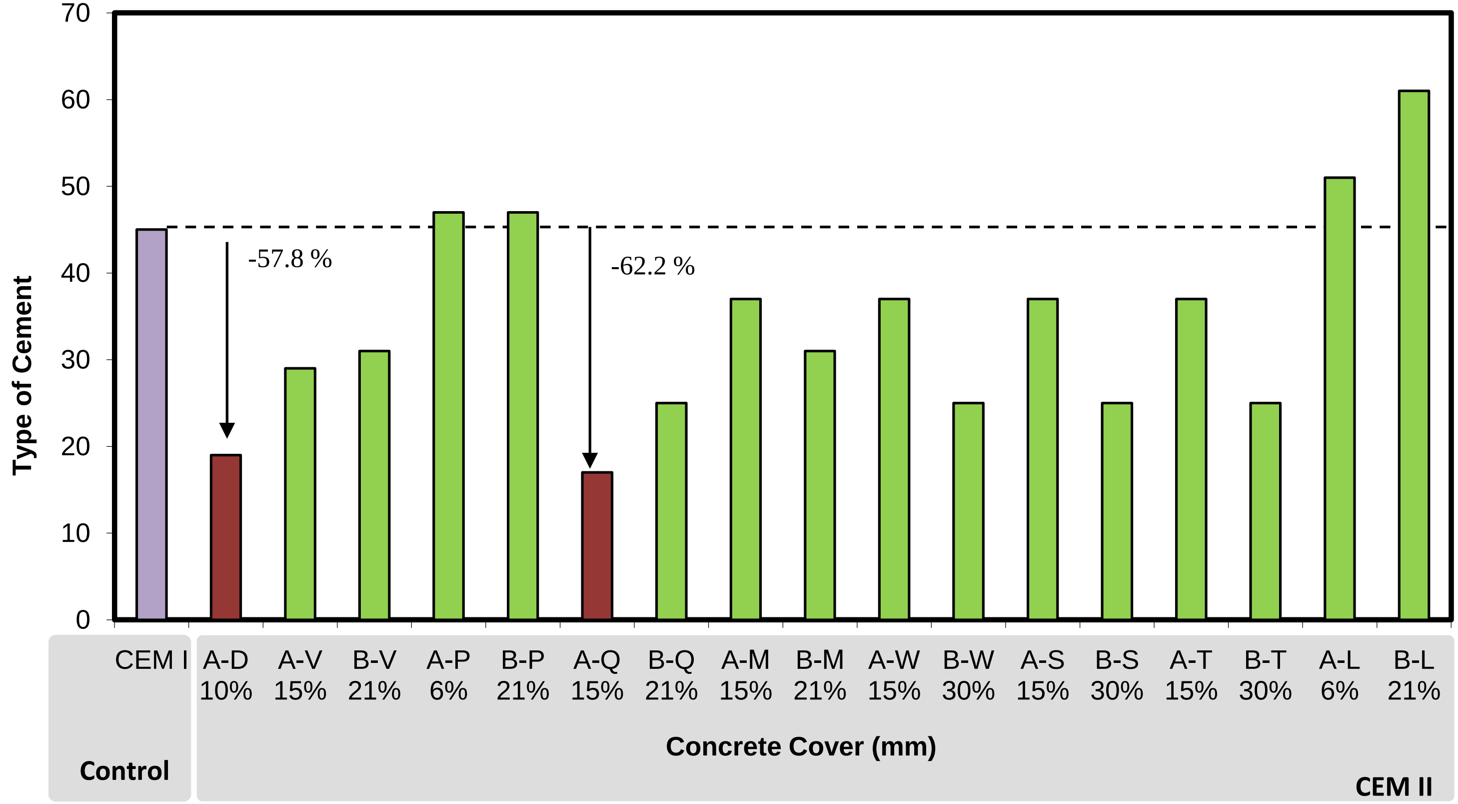
(A) 6-20% SCM in CEM II (6-10% for silica fume), 36-64 % in CEM III, 11-35% in CEM IV, 18-30% in CEM V
(B) 21-35% for CEM II, 66-80% for CEM III, 36-55% for CEM IV and 31-50% for CEM V

(D) silica fume	(V) siliceous fly ash	(W) calcareous fly ash	(P) natural pozzolana
(Q) artificial pozzolana	(S) blast furnace slag	(T) burnt shale	(L) limestone
(M) other composite material			

- Increased carbonation depths of every CEM II type of cements
  - Mainly attributed to low portlandite content and subsequent reduction of $Ca(OH)_2$ from pozzolanic activity.

- Certain types of cement produced more tolerable behaviour.
  - At low SCM concentration, pozzolanic action and filling properties of SCM afford certain changes in porosity which predominate over reduction in carbonatable materials leading to less severe carbonation effect.

Utilisation – Effect of CEM II cements on service life (chlorides)

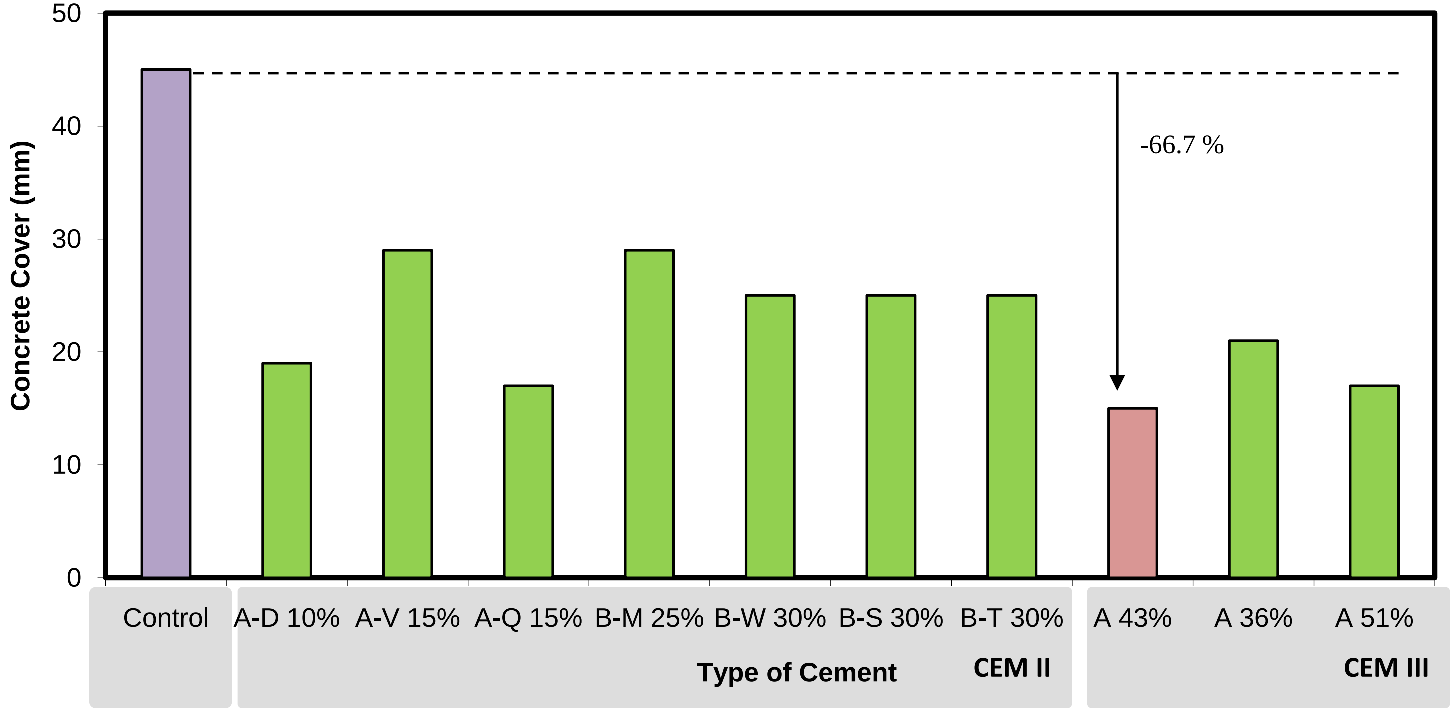


- Under chloride exposure every different type of Portland-composite cement used behaved in an extraordinary way.

- Cement incorporating 15 % artificial pozzolana (CEM II/A-Q) produced the best performance (reductions of up to 62.2 % on the concrete cover and 92.9 % reduction of the chloride ions diffusivity)

- Cements containing blast furnace slag (S) produced the best performance, overall, at low (6 % - 15 %) and high (21 % - 30 %) quantities of SCM.

Utilisation – Effect of CEM III cements on service life (chlorides)



Comparing the best behavior of CEM II and CEM III type of cements it can be seen that a 43% blast furnace cement (CEM III) produced the best performance in designing for chloride exposure (at 50 years) than any other CEM II type of cement.

Conclusions

- **A simulation tool for the estimation of concrete compressive strength class and service life**, based on proven predictive models according to performance related methods has been developed and verified.

•The tool presented offers a comprehensive approach on **concrete service life estimation**, in terms of:

- Defining the concrete mix design and the main chemical/volumetric characteristics of concrete
- Estimating the compressive strength class
- Accurately predicting the concrete service life, for carbonation and chloride exposure, by taking under consideration the relative exposure classes and by utilising sophisticated proven predictive mathematical models of the physicochemical processes leading to such deterioration

- **By utilising the simulation tool, a comparative assessment of all SCM incorporated in cement took place.**

- Taking into account the reduction in clinker achieved when an **SCM** is utilized and the overall performance of these materials presented in this study, utilisation of these types of cement not only can guarantee a durable solution (under harmful environmental agents) but they also **provide a sustainable solution**, by reducing the CO_2 emissions associated with the clinker burning process during cement manufacturing.

- **It is hoped that the focus of this study will initiate a wider acceptance of software based predictive models in achieving a feasible and durable solution, possible by incorporating them in next generation standards (EN-206).**

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