Computer – Based Estimation of Concrete Service Life

by V. G. Papadakis and M. P. Efstathiou

Synopsis: Over the past 50 years, an enormous amount of effort has been expended in laboratory and field studies on concrete durability. The results of this research are still either scattered widely in the journal literature or mentioned briefly in the popular 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 could be the development of appropriate software for computer-based estimation of concrete service life, including reliable mathematical models and adequate supporting experimental data.

In the present work, the basis for the development of a computer estimation of the service life of reinforced concrete is presented. Based on concrete mixture proportions and structure characteristics, as well as the environmental conditions where the structure will be found, service life can be reliably predicted using fundamental mathematical models that simulate the deterioration mechanisms. The prediction is focused on the basic deterioration phenomena of reinforced concrete, namely carbonation and chloride penetration. Aspects related to concrete strength and production cost are also considered. This approach enables mixture proportions to be accurately specified and concrete performance predicted reliably.

Keywords: concrete, durability, estimation, modeling, service life, software.

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INTRODUCTION

Despite significant advances made in concrete technology in recent years, the problems of unsatisfactory durability of structures are in a dramatic increase. Deterioration of concrete in service may be the result of a variety of mechanical, physical, chemical or biological processes.[1-5] Corrosion of steel reinforcement is the most serious durability problem of reinforced concrete structures. It impairs not only the appearance of the structure, but also its strength and safety, due to the reduction in the cross-sectional area of the reinforcement and to the deterioration of bond with the surrounding concrete. Over the past decades, an enormous amount of energy has been expended in laboratory and field studies on concrete durability. The results of this research are still either scattered widely in the journal literature or mentioned briefly in popular textbooks; having although included in the relevant industry consensus documents as well as in the relevant codes for construction. 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 could be the development of appropriate software for computer estimation, including reliable mathematical models and strengthened by adequate experimental data.

In the present work, a mixture proportioning strategy to fulfil requirements for 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 developed earlier mostly by the senior author. The prediction focuses on the basic deterioration phenomena of reinforced concrete, carbonation and chloride penetration. Aspects on concrete strength and production cost are also considered. The proposed models enable mixture proportions to be specified accurately and concrete performance predicted reliably. In general, this work is aimed at construction engineers and building material manufacturers to enhance fundamental comprehension of materials behavior. Basic principles of chemical engineering are applied to simulate the physicochemical processes, yielding simple and accurate mathematical models for design and prediction. The work approach presented herein is in full compliance with the new European Standards, for cement: EN 197, and concrete: EN 206;[6, 7] however, after a short modification it can be applied to any other similar national standard.

CONCRETE DURABILITY AND THE EUROPEAN STANDARD EN 206 APPROACH

The type and rate of degradation processes of concrete and reinforcement determine the strength and the rigidity of the elements that compose the structure. These affect the safety, the serviceability, and the appearance of a structure, i.e., determine the performance of the structure. Concrete service life (or working life) is the period of time during which the performance of the concrete structure will be kept at a level compatible with the fulfilment of the performance requirements of the structure, provided it is properly maintained. The ability of a structure to resist environmental attacks, without its performance dropping below a minimum acceptable limit, is called durability. The following three main factors affect the durability of concrete: the initial mixture proportions, the design, construction and maintenance of the structure, and the specific environmental conditions. Deterioration of concrete in service is every loss of performance, and it may be the result of a variety of mechanical, physical, chemical or biological processes,[1-5] see Fig. 1.

The European Standard EN 206[6] specifies requirements for the constituent materials of concrete, the properties of fresh and hardened concrete and their verification, the limitations for concrete composition, the specification of concrete, the delivery of fresh concrete, the production control procedure, the conformity criteria, and evaluation of conformity. It defines tasks for the specifier, producer, and user. During its development, consideration was given to detailing a performance-related approach to the specification of durability, but it was concluded that test methods to specify durability are not yet sufficiently developed to include them in the standard. However, this standard permits the continuation and development of performance-related methods for assessing durability, as does the present paper.

According to EN 206, environmental actions are those chemical and physical actions to which the concrete is exposed and that result in effects on the concrete or reinforcement or embedded metal that are not considered as loads in structural design. The main deterioration actions considered are corrosion of reinforcement induced either by carbonation or chlorides, cyclic freezing and thawing, and chemical attack. The environmental actions are classified in exposure classes;[6] their selection depends on the provisions valid where concrete will be used. Durability is then specified either through the traditional practice of limiting values of concrete composition (more widely used) or by performance-related methods. The requirements shall take into account the intended service life of the concrete structure.

Limiting Values for Concrete Composition

In the absence of European standards for absolute performance testing of concrete, requirements for the method of specification to resist environmental actions are given in EN 206 in terms of established concrete properties and limiting values for concrete composition. The requirements for each exposure class shall be specified in terms of permitted types and classes of constituent materials, maximum water-cement ratio, minimum cement content, minimum concrete compressive strength class (optional), and, if relevant, minimum air-content of the concrete.

Due to lack of experience on how the classification of the environmental actions on concrete reflect local differences in the same nominal exposure class, the specific values of these requirements for the applicable exposure classes are given in the provisions valid in the place of use. A recommendation for the choice of limiting values for concrete composition and properties is given in Annex F (informative) of EN 206. These values are based on the assumption of an intended service life of the structure of 50 years, and refer to the use of cement type CEM I conforming to EN 197.[7]

Performance-related Design Methods

Guidance on the use of an alternative performance-related design method with respect to durability is given in Annex J (informative) of EN 206. The application of an alternative method depends on the provisions valid in the place of use of the concrete. The performance-related method should consider each relevant deterioration mechanism, the service life of the element or structure, and the criteria which define the end of this service life, in a quantitative way. Such a method may be based on satisfactory experience with local practices in local environments, on data from an established performance test method for the relevant mechanism, or on the use of proven predictive models.

The direction of the present work is towards the development of performance-related methods based on predictive models that have been calibrated against test data representative of actual conditions in practice.

MODELLING OF DETERIORATION RATE AND COMPUTER DESIGN

As observed in Fig. 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. Chemical and biological mechanisms actually start from the beginning; however, their detrimental results are observed typically 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. It is therefore necessary, if a long service life is required, that the modelling attempts to address corrosion initiation mechanisms and chemical/biological attack processes.

Fig. 2 shows the logic diagram followed in the software program development[8] for the estimation of concrete service life. First, the essential parameters that characterize a concrete composition (mixture proportions) are selected, and this is the main source on which all other concrete characteristics depend. Thereafter, 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 mixture proportions (cement type and strength class, cement content, water-cement ratio, air content, aggregate type, type and activity of additions, etc.), the compressive strength class of concrete is estimated.[9]

For each significant deterioration mechanism, according to the specific environment where the structure would be found, an appropriate proven predictive model is used.[9-13] 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, which cause either carbonation or chloride penetration, is calculated. The degree of deterioration from a possible chemical attack is also estimated, either as a reduction in the effective concrete section (in the case of acid or biological attack) or as a reduction in strength of the affected concrete (in the case of sulphate or alkali attack). Finally, cost and environmental aspects regarding concrete composition are 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 the concrete composition accordingly to improve further every required property. In the following, typical results are presented concerning various exposure classes and compositional parameters.

Reinforcement Corrosion Induced by Carbonation

Reinforcing bars in concrete are protected from corrosion by a thin oxide layer that forms on their surface due to the high alkalinity, i.e., the high pH-value, of the surrounding concrete. Corrosion may start when this protective layer is destroyed:

- either by chloride penetration (and the chloride content exceeds a critical value), or
- due to a reduction in the pH value of concrete to values below 9. Such a reduction in alkalinity is the result of carbonation of the $Ca(OH)_2$ in the concrete mass, i.e., of its reaction with the atmospheric CO_2 that diffuses through the concrete pores.

Papadakis et al.[10, 11] were the first to develop a reaction engineering model of the processes leading to concrete carbonation, yielding a nonlinear system of differential equations in space and time that must be solved numerically. For the usual range of parameters, certain simplifying assumptions can be made, which lead to the formation of a carbonation front; the evolution of this is given by a simple analytical expression.[10, 11]

This approach is the basis in the software[8] for estimation of the corrosion-initiation period.

In reinforced concrete structures, it can be reasonably assumed that major repair will be necessary once corrosion of the reinforcement causes generalized cracking of the concrete cover, signalling the end of the service life of the structure. The time required to crack the concrete cover is equal to the time required for the carbonation front to reach the bar (period to initiation of corrosion, $t_{cr,carb}$) plus the time necessary for the layer of rust to build up around the bar and split the cover (corrosion propagation period, $t_{pr,carb}$). According to various researchers,[14, 15] the corrosion rate in carbonated concrete at high relative humidity values is so high that the arrival of the carbonation front at the bar is followed shortly by splitting of the concrete cover. Therefore, the time $t_{cr,carb}$ required for the carbonation front to penetrate the concrete cover, c, can be considered with good approximation as a lower bound (minimum) to the service life of reinforced concrete.

Corrosion is much faster than carbonation at higher water contents of concrete pores, and consequently at higher relative humidity (RH) of the ambient air. This was taken into account in the definition of the exposure classes in EN 206. We propose to use a measurable characteristic of the environment regarding its humidity state, i.e., the mean RH, in order to convert the somehow indefinite exposure classes of EN 206. In order to investigate if the EN 206 recommendations for limiting composition values would ensure a service life of 50 years, the above software[8] was used, and the results are presented in Table 1. Various cement compositions were examined for concrete production, using common crushed aggregates of maximum nominal size of 31.5 mm. We assume a non-protected concrete surface, exposed to an urban environment (CO_2-content: 0.08%).

For the exposure class XC1 (dry environment; we propose: 45%≤RH<65%, with a mean value of 55%), carbonation is more rapid, however, in this region the corrosion rate is low due to insufficient moisture. According to Parrot,[14] the critical corrosion depth of the reinforcing bar that causes visible deterioration is 100 μm, and as the corrosion rate is about 0.3 μm/y in this RH region, the propagation period is $t_{pr,carb}$>100 years. A typical example of this case is the concrete inside buildings or structures where the RH remains low during the whole working life. For the same exposure class, XC1, but for permanently wet environment (we propose: RH≥98%, value used for computations= 98%), carbonation is almost fully inhibited due to water-filled pores which decrease significantly the CO_2 diffusion, and the corrosion process is also very slow for the same reason, as regards O_2 diffusion. Typical examples of this case are concrete members that will be submerged at all times during the working life.

For the exposure class XC2 (wet, rarely dry, we propose: 90%≤RH<98%, value used for computations= 90%), both the carbonation and corrosion rates are greater than in the XC1 environment (permanently wet), however for the compositional parameters of Table 1, the $t_{cr,carb}$ is almost 100 years. Typical examples of this case include concrete reservoirs and water towers that will be full most of the time, and foundation members below ground level.

For the exposure class XC3 (moderate humidity, we propose: 65%≤RH<85%, value used for computations= 70%) carbonation is faster than XC2, and lower than XC1 (dry environment). For a concrete cover to reinforcement c=40 mm and the mixture proportions of Table 1, $t_{cr,carb}$>200 years for CEM I and much lower for CEM II/A-M, $t_{cr,carb}$=140-170 years, for CEM II/B-M, $t_{cr,carb}$=80-110 years, and for CEM IV/B, $t_{cr,carb}$=50-60 years.[8] The corrosion rate is also high due to presence of both oxygen and water. In such an environment of high humidity, the corrosion rate[4, 14] is almost 5-20 μm/y, which gives propagation periods of the order of 5-20 years (as 100 μm is the critical corrosion depth). Morinaga,[15] estimates even a shorter period of 2 years! Typical examples of this case are external concrete surfaces sheltered from rain and internal concrete with higher than normal relative humidity. As these exposure conditions are rather common, and the corrosion rate is high enough, more onerous limiting values for concrete composition have to be applied, than those recommended by EN 206, as also proposed in British Standard BS 8500.[4, 16]

For the last exposure class XC4 (cyclic wet and dry, we propose: 75%≤RH<90%, with a mean value of 80%) carbonation rate is still medium due to dry periods. The corrosion rate is at its maximum level due to the presence of both oxygen and adequate water. It has also to be emphasized that concrete takes water from the environment more rapidly than it loses it and thus the internal humidity could be higher than the average ambient humidity. This higher internal moisture speeds up the corrosion rate. Typical examples of this case are external concrete surfaces exposed to rain and many other, mostly industrial, applications.

Reinforcement Corrosion Induced by Chlorides

Numerous surveys have indicated that penetration of chloride ions (Cl^-), originating from de-icing salts or seawater, is the primary cause of reinforcing steel corrosion in highways and marine or coastal structures.[3, 5, 9] Chlorides transported through the concrete pore network and microcracks depassivate the oxide film covering the reinforcing steel and accelerate corrosion and concrete deterioration.

Papadakis et al.[12, 13] presented a generalized model of chloride diffusion and reaction in saturated or non-saturated concrete. This model can be solved only numerically, e.g., using a finite difference or element method, as does the software.[8] The solution allows estimation of the time (critical time for chloride-induced corrosion, $t_{cr,chlor}$) required for the total chloride concentration surrounding the reinforcement (located at a distance c from surface) to increase over the threshold for depassivation. The threshold may be expressed in terms of the total chloride ion content in concrete required for the onset of reinforcement corrosion, and a mean value of 0.8% by mass of cementitious materials is adopted.[9, 17]

Chloride penetration takes place in totally or partly water-filled pores. This is the main reason that the process is much slower than carbonation, where CO_2 molecules may penetrate faster via air-filled pores. The RH of the environment and the origin of Cl^- were taken into account in the definition of the exposure classes in EN 206. In order to investigate whether the EN 206 recommendations for limiting composition values would ensure a service life of 50 years, the above software[8] was used (see a typical overview in Fig. 3) The results are presented also in Table 1 for these exposure classes: XS1: exposed to airborne salt but not in direct contact with sea water (structures near to or on the coast), XS2: permanently submerged (parts of marine structure), XS3: tidal, splash and spray zones (parts of marine structure). The same cement compositions were examined, using common crushed aggregates of a maximum size of 31.5 mm. For all exposure classes, we assume a non-protected concrete surface, exposed to Atlantic Ocean environment (Cl^- concentration of 20 kg/m^3).

In the case of concrete containing reinforcement and subjected to contact with chlorides from sea water, the recommendations of EN 206 ensure a service life greater than 50 years (even 100 years) for almost all exposure classes and for an adequate cover. The only exception concerns the XS2 exposure class where lower than 50 years for the depassivation period is estimated; however, in this case of permanently submerged concrete the corrosion rate of the depassivated steel is extremely slow and thus the total service life is much longer than the lower bound of the depassivation period. In the case also of the exposure class XS3, a depassivation period shorter than 50 years is observed for cement compositions either poor in clinker or in pozzolanic materials. It has to be emphasized that contrary to the carbonation results, cement types that contain supplementary cementing materials (silica fume, pozzolana, fly ash, etc.) exhibit significantly longer initiation periods than normal portland cement; however, this improvement goes through a maximum as portland cement is reduced.

CONCLUSIONS

Computer software,[8] based on proven predictive models, has been developed for estimation of concrete service life, strength and cost, and it may be included in performance-related methods of EN 206 for assessing durability. Its structure is in full compliance with the European Standards EN 197 for cement (applicable to all 27 types of cement) and EN 206 for concrete (including addition use, such as silica fume and fly ash, various admixtures use, etc.). The logic diagram, however, can be developed for any other national standard. The software offers the possibility of investigating the efficiency of various protection measures, such as waterproof sealants, cement-lime mortar coatings, inhibitors, etc. Comparing the software results with the recommendations of EN 206 for common exposure classes, a general agreement is observed, but also several adjustments are still required.

The introduction of performance-related design methods, such as proven predictive models in the form of user-friendly software, is absolutely necessary[6] when:

- a service life significantly differing from 50 years is required;
- the structure is "special" requiring a lower probability failure;

- the environmental actions are particularly aggressive, or are well defined;
- a particular management, maintenance or protection strategy is to be introduced;
- significant populations of structures or similar structures or elements are to be built;
- new or different constituent materials are to be used; and
- a method based on limiting values for concrete composition has been used in design, but there has been a failure to conform.

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Table 1 - Estimated minimum concrete service life for various cement compositions and exposure classes, in the cases of carbonation- (XC3) or chloride- (XS1-XS3) induced corrosion of reinforcement.[8]*

Limit	**XC3**	**XS1**	**XS2**	**XS3**
max W/C	0.50	0.50	0.50	0.45
min cement content, C (kg/m^3)	300	330	330	350
min cover, c (mm)	40	40	40	45

	Composition of cement (% by mass)			**Period for reinforcement depassivation (t_{cr}, years) ≥**			
No	**Clinker**	**Pozzolana + fly ash**	**Lime-stone**	**XC3**	**XS1**	**XS2**	**XS3**
1	55	40	5	48	44	9	20
2	60	35	5	61	70	15	33
3	65	30	5	80	> 100	26	70
4	70	25	5	103	> 100	37	> 100
5	70	15	15	90	100	21	50
6	75	20	5	123	> 100	37	100
7	75	10	15	104	87	18	46
8	75	15	10	111	> 100	24	63
9	80	15	5	137	> 100	26	70
10	85	10	5	158	> 100	22	62
11	85	5	10	146	82	17	42
12	90	5	5	179	94	21	53
13	90	0	10	168	73	16	38
14	95	0	5	> 200	79	18	45

*W/C: water to cement ratio by mass, C: cement content in concrete, c: concrete cover to reinforcement, t_{cr}: initiation period for carbonation- or chloride induced corrosion of reinforcement.

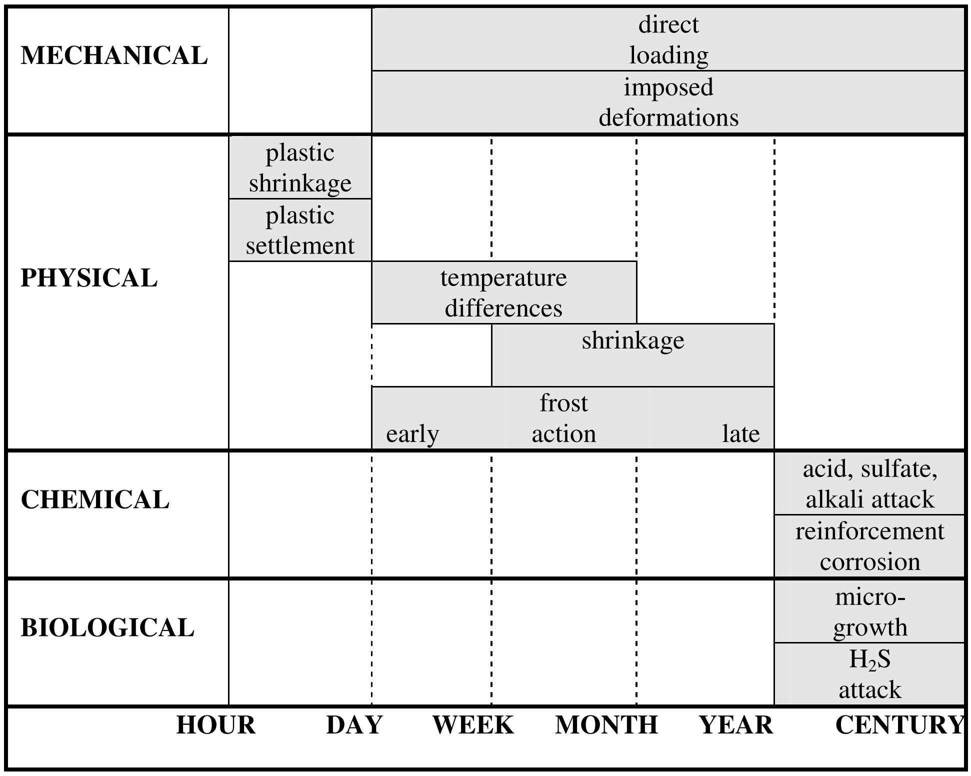

Fig. 1. Deterioration mechanisms and possible time of appearance of cracking or damage

CONCRETE MIXTURE PROPORTIONS

INPUT

Cement (Cement type according to EN 197, standard and early strength class. Composition in clinker, other main constituents, minor constituents, and gypsum. Cement density and 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, additions 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 and content)

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

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

CALCULATION (Aggregate content, fresh concrete density)

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CHEMICAL AND VOLUMETRIC CHARACTERISTICS OF CONCRETE

INPUT

Cement composition and oxide analysis (Oxide analysis of clinker, oxide analysis and activity of other main constituents of cement, oxide analysis and activity of silica fume and fly ash)

CALCULATION (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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CONCRETE STRENGTH	**CONCRETE LIFE REGARDING CARBONATION**	**CONCRETE LIFE REGARDING CHLORIDE PENETRATION**	**CONCRETE LIFE REGARDING CHEMICAL ATTACK**	**COST AND ENVIRON-MENTAL ASPECTS**
Calculation (Mean compressive strength, strength class, strength ratio 2/28 days, strength development)	**INPUT** **Environmental 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)	**INPUT** **Environmental conditions** (exposure class, relative humidity, Cl^- concentration) **Initial-boundary conditions. Threshold for corrosion.** **Calculation** (For specific cover and protection: corrosion-initiation period)	**INPUT** **Environmental conditions** (exposure class, relative humidity, type of deteriorating agent and concentration) **Calculation** (For specific agent and protection measures: total service life)	**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)

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TECHNICAL AND ECONOMICAL OPTIMIZATION

Mixture proportions optimization to achieve the specified strength and durability at the lowest cost.

Fig. 2. Logic diagram for computer-based estimation of concrete service life

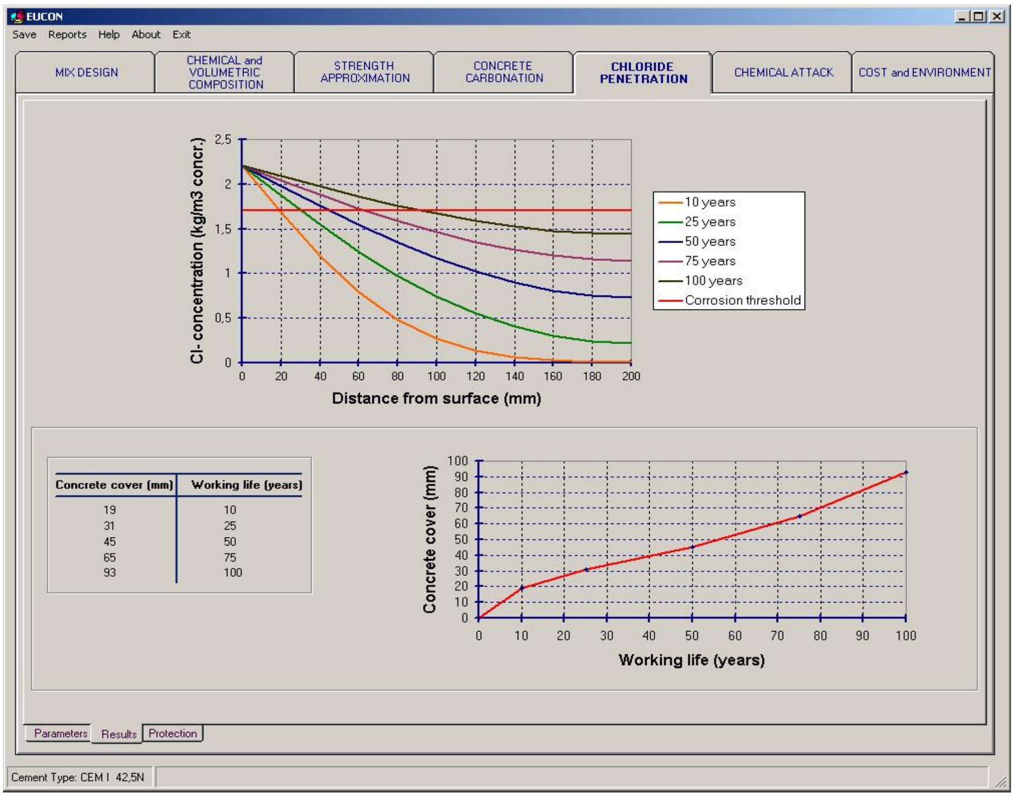

Fig. 3. General view of the tab “CHLORIDE PENETRATION” of the EUCON® program