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Estimation and Validation of Concrete Strength and Service Life Using Software Packages based on Predictive Models

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ABSTRACT

Despite the high level of research and the significant advances achieved in concrete technology, issues of unsatisfactory durability of structures are a major concern of the international engineering community. The observed deterioration of concrete structures in service may be perceived as the result of the joint action of mechanical and environmental effects. Corrosion of steel reinforcement is recognised as the most serious outcome of these actions, impairing not only the appearance of the structure, but also its strength and safety. A correct selection of the raw building materials, a systematic construction process but most importantly a thorough durability design process that identifies the influence of the harmful environmental agents, in a way that the designer can take all the appropriate measures (in advance) to mitigate their influence, is the only way to safeguard a prolonged service-life of any type of structure. On this note, a significant step forward is the development of appropriate software packages, based on predictive models, for the estimation of concrete strength and service life.

In this study, a step by step procedure, previously developed (in full compliance with the European Standards EN 197 for cement and EN 206 for concrete), based on analytical mathematical models for the estimation of concrete service life and strength, is briefly presented. Validation of the estimated strength and service life results is taking place using a wide range of data collected throughout the recently published literature and from field observations and existing structures. 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.

KEYWORDS
Predictive Models, Concrete Strength, Service Life, Carbonation, Durability

INTRODUCTION

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While recognising the problem of premature structural deterioration of reinforced concrete (RC) structures as a combined effect of mechanical and environmental actions (diffusion of carbon dioxide from the atmosphere, ingress of chlorides), emphasis is given from a durability point of view on the effect of the latter, in understanding the physiochemical processes and mechanisms leading to the reduction of an RC element service life. However, approaches on modelling the deterioration mechanisms, presented so far, are usually limited to complicated mathematical models not widely applicable in practice. What is missing is a set of toos that will aid the designer in identifying the influence of the harmful environmental agents, in order to take all the appropriate measures (in advance) to mitigate their effect, in safeguarding a prolonged service-life of any type of structure.

Considering that on the European Standard for concrete EN 206 [2000] durability is approached either through the definition of limiting parameters on the cement and concrete composition (w/c ratio, cement content, etc.) or through the continuation and development of performance-related methods, a significant step forward could be the development of appropriate software for the estimation of concrete service life, based on the principles of these methods, using reliable mathematical proven models and strengthened by adequate experimental data. A performance-related method considers each relevant deterioration mechanism, the service life of the structure, and the criteria which define the end of this service life, in a quantitative way. Such a method may be based on data derived from established performance test methods for each relevant mechanism, or on the use of proven predictive models. Bearing in mind that in reinforced concrete, the most serious deterioration mechanisms are those leading to corrosion of the reinforcement, it is therefore necessary, if a long service life is required, the modelling attempts to focus on these mechanisms and chemical attack processes.

In this study, a simulation tool, based on proven predictive models developed by Papadakis et al. [1981; 1992; 2007] well published and awarded by the ACI, for estimation of concrete service life and strength (according to in performance-related methods of EN 206 for assessing durability) is briefly presented and verified. Its structure is illustrated in Fig. 1.

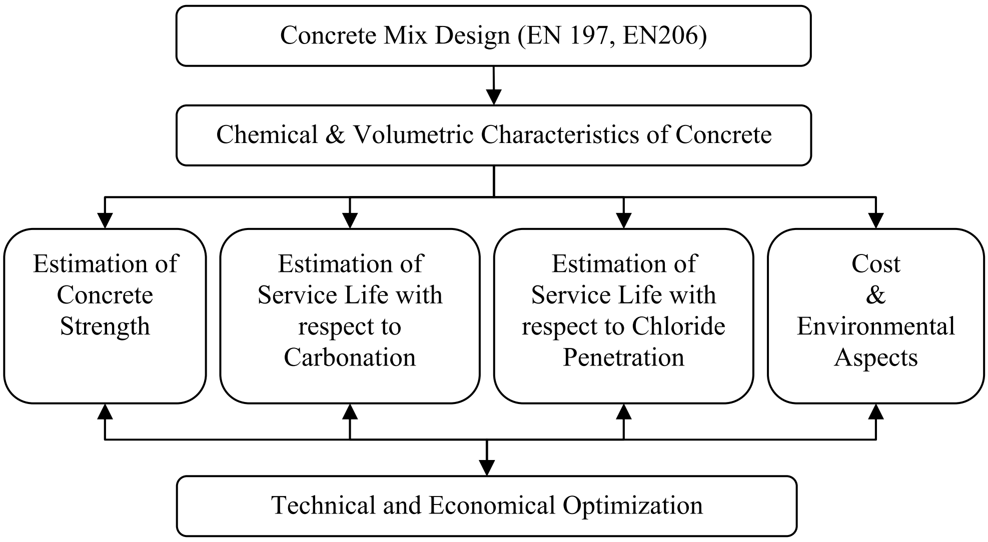

Figure 1.
Logic tree of software for estimation of concrete service life and strength

After the definition of the concrete mix design and the calculation of the main chemical and volumetric characteristics of concrete (chemical composition of hydrated cementitious materials, porosity and related characteristics) the compressive strength is estimated, introducing a new approach based on the cement strength class, using a modified version of Feret's formula. By taking into account the environmental conditions where the structure will be exposed, the concrete service life is reliably predicted using fundamental mathematical models that simulate the basic deterioration mechanisms of reinforced concrete, such as carbonation and chloride penetration. Principles of chemical and material engineering have been applied to simulate the physicochemical processes [Papadakis et al. 1989]. Finally, cost and environmental aspects on concrete composition are analysed.

2 COMPRESSIVE STRENGTH AND SERVICE LIFE ESTIMATION

In this section the thoughts behind the compressive strength and service life estimation, for carbonation exposure, are briefly presented. The reader should bear in mind that these attempts have been published extensively elsewhere [Papadakis et al. 1981; 1992; 2007; Papadakis, 2000].

2.1 Compressive Strength Estimation

Usually most of the equations found in the literature relating compressive strength to the concrete constituents are of an empirical nature, and can not be applied in general. Furthermore, considering that the effect of each component of hydrated cement on strength is not just additive, as well as bearing in mind their dependence on age and curing conditions and their various interactions, it becomes apparent that a generally applicable strength prediction is not possible. On this note, but more important due to the lack of experimental results, the cement strength class can be used to estimate a safe lower limit of concrete strength. The European Standard EN 197-1 [2000] prescribes a compressive strength test for cement on mortar specimens of fixed composition. By incorporating the information mentioned in the Standard to Feret's formula (the most well recognised strength equation relating compressive strength to concrete characteristics), since it contains only one adjustable parameter a safer approximation of the minimum compressive strength class of concrete (at 28 days) can be derived for different values of W/C, C or ε_{air} as:

$$f_c \geq 7.84\, S_c / [1 + (W/C)(d_C/d_W) + \varepsilon_{air}(d_C/C)]^2 \qquad (1)$$

where C and W are the cement and water contents in concrete (kg/m^3 concrete), d_C and d_W the densities of cement and water respectively (kg/m^3), ε_{air} the air content in concrete, and S_c is the standard strength class (at 28 days) of cement (MPa).

If a strength result from the above mentioned mortar specimens is known at another age (2, 7, or 90 days), it can be used in the above equation as S_c, in order to estimate the compressive strength at the same age and for other W/C values. In this way, the strength development can be predicted. In the case of SCM-concrete, the pozzolanic action of the addition is taken under consideration (since it generates strength components) using the concept of the SCM efficiency factor. The latter (or k-value) is defined as the part of the SCM that can be considered equivalent to portland cement (CEM I), providing the same concrete properties (k=1 for portland cement) [Papadakis, 2000]. In this way, the compressive strength can be estimated as:

$$f_c \geq 7.84\, S_c / \{1 + [W/(C+k_F F_{ACT}+k_S S_{ACT})](d_C/d_W) + \varepsilon_{air}[d_C/(C+k_F F_{ACT}+k_S S_{ACT})]\}^2 \qquad (2)$$

where F_{ACT} and S_{ACT} are the active contents of concrete additions fly ash and silica fume (kg/m^3), having an efficiency factor k_F and k_S respectively.

2.2 Estimation of Service Life for Carbonation Exposure

Based on reaction engineering principles, a system of non-linear differential equations, developed by Papadakis et al. [1989; 1991] models in a quantative way the processes leading to concrete carbonation (diffusion of CO_2 in the gas-phase of pores, its dissolution in the aqueous film of these pores, the dissolution of solid $Ca(OH)_2$ in pore water, its ultimate reaction with the dissolved CO_2, and the reaction of CO_2 with CSH). The solution of the set of differential equations permits the calculation of the carbonation depth x_c, at a given time t, as well as the estimation of the critical time, $t_{cr,carb}$, required for the carbonation front to reach the reinforcement located at a distance *c* (concrete cover to reinforcement), for both portland and blended cements, as well as when additions of SCM are used separately in concrete:

$$x_c = \sqrt{\frac{2D_{e,CO2}(CO_2/100)t}{0.33CH + 0.214CSH}}, \quad t_{cr,carb} = \frac{(0.33CH + 0.214CSH)c^2}{2D_{e,CO2}(CO_2/100)} \tag{3}$$

where, CO_2 is the CO_2-content in the ambient air at the concrete surface (%), $D_{e,CO2}$ the effective diffusivity of CO_2 in carbonated concrete (m^2/s), *CH* and *CSH* the contents of calcium hydroxide and calcium-silicate-hydrate, respectively, in concrete volume (kg/m^3). In this way the service life of a concrete structure, regarding corrosion of reinforcement induced by carbonation, is at least $t_{cr,carb}$.

3 EXPERIMENTAL VERIFICATION

3.1 Verification of Compressive Strength Predictions

As far as strength estimation is concerned, a two step verification process took place, based on data collected from ready-mix plants and from the literature. Characteristic examples of these sets of data, as well as their overall comparison with the compressive strength values, calculated using the equations described above, are presented in this section.

3.1.1 Comparison with experimental results from ready-mix plants

The experimental results gathered, concern strength measurements of CEM I and CEM II/B-M specimens of compositional studies from various worksites and ready-mix factories throughout Greece. Depending on the w/c ratio, various cement contents have been used (from 200 to 500 kg/m^3) without any active additions (fly ash, silica fume, etc.). Crushed aggregates of a maximum grain size of 31.5 mm were used, and a mean air-content of 1.2 % (representative in most cases) was assumed. As shown in Fig. 2a, an excellent agreement is observed between strength measurements and predictions, based on the previously described Equation (1), for the CEM I / 42.5 cement type. The cement strength class for these specimens (i.e., the S_c parameter of Equation 1) was 42.5.

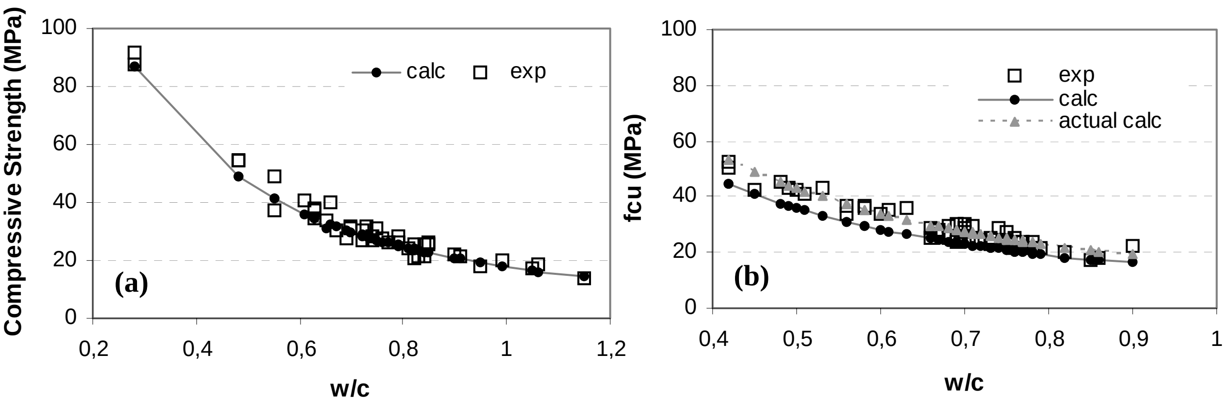

Figure 2. Comparison between predictions of the 28 days-compressive strength and experimental measurements of CEM I / 42.5 and CEM II/ 32.5 type of cements.

In the case of CEM II/32.5 type of specimens (Fig. 2b), a first quick observation can be translated as a slight underestimation, especially for the range of w/c ratios from 0.4 to 0.62 (even though it is not far from the aim of this study in estimating a safe lower limit of concrete strength). The reason that these predictions constitute a safe lower bound, is that the real cement strength is higher than the nominal cement strength class (the Greek cement factories usually, for this type of cement, produce higher cement strength than the nominated one due to underestimation of active additions of the cement).

Bearing the latter in mind, and based on the real mortar strength at 28 days (39 MPa, instead of 32.5 MPa), the previously mentioned "safe lower limit" or compressive strength can be re-calculated to approach in a more accurate way the compressive strength of concrete at 28 days. It can be seen that the "actual" values of the estimated concrete compressive strength of the CEM II / 32.5 samples are in a very good agreement with the experimental results (Fig. 2b).

3.1.2 Comparison with literature-based data

At the second verification stage of the compressive strength estimation, validation using data obtained from the literature was achieved. A significant amount of experimental data were collected concerning CEM I type of cements, CEM I with Type II additives (silica fume, fly ash), CEM II and III type of cements. The chemical composition of each type of cement (where given) and Type II additive (where used) were incorporated in the calculations. In cases where the air content was not given, it was calculated based on the maximum grain size of aggregates, using linear interpolation between the air content values of aggregate sizes of 31.5 mm, 16 mm and 8 mm, as 1.5 %, 2.3 % and 3.5 % respectively. A wide range of w/c ratios was covered (from 0.3 to 0.9). Representative sets of data and the corresponding results are given in Table 1.

Table 1. Characteristic compressive strength estimation sets of data obtained from the literature

Reference	Cement Type	S_c	C *(kg/m^3)*	F *(kg/m^3)*	w/c	ε_{air} *(%)*	f_c exp *(MPa)*	f_c calc *(MPa)*
Kockal & Turker, 2007	CEM I	42.5 N	340	-	0.45	1.8	50.9	49.9
Liu, 2010	CEM I	42.5 N	245	105	0.83	1.5	31.4	30.4
Kockal and Turker, 2007	CEM II/B-M	32.5 R	340	-	0.41	1.8	45.2	42.2
Climent et al., 2002	CEM II/A-L	32.5 R	350	-	0.6	3.3	27.9	25.1
Tsivilis et al., 2003	CEM II/B-L	32.5 R	333	-	0.62	2.3	26.5	25.3

f_c exp, f_c calc are the compressive strength values from the literature and those calculated from the model

The comparison for every type of cement used between the estimated and the experimental compressive strength values is illustrated in Fig 3. A mean variation of 6.0 % was observed for the CEM I, CEM I with Type II additives and CEM II sets of data. Overall the new proposed method for estimation of the concrete compressive strength, based on cement strength class (S_c), offers an accurate prediction on any type of cement used, incorporating or not Type II additives.

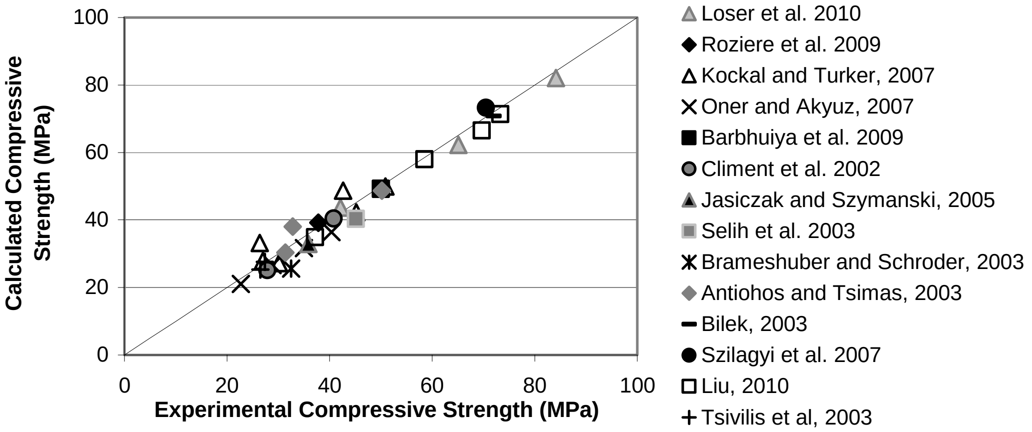

Figure 3. Comparison of experimental with calculates values of concrete compressive strength data

3.2 Verification of Service Life Prediction for Carbonation Exposure

Carbonation depth results were collected from the recent published literature, under either accelerated conditioning or natural ageing, for different exposure times. Parameters as cement type, mix design characteristics, chemical composition of the clinker and pozzolanic materials, levels of relative humidity and carbon dioxide concentration (where the reinforced concrete element was exposed) were recorded and inserted into the model developed by Papadakis et al. [1991; 2007]. The calculated carbonation depth values were compared with the corresponding values taken from the literature (Fig. 4). A very good correlation was observed (an average variation of 7.6 % was calculated).

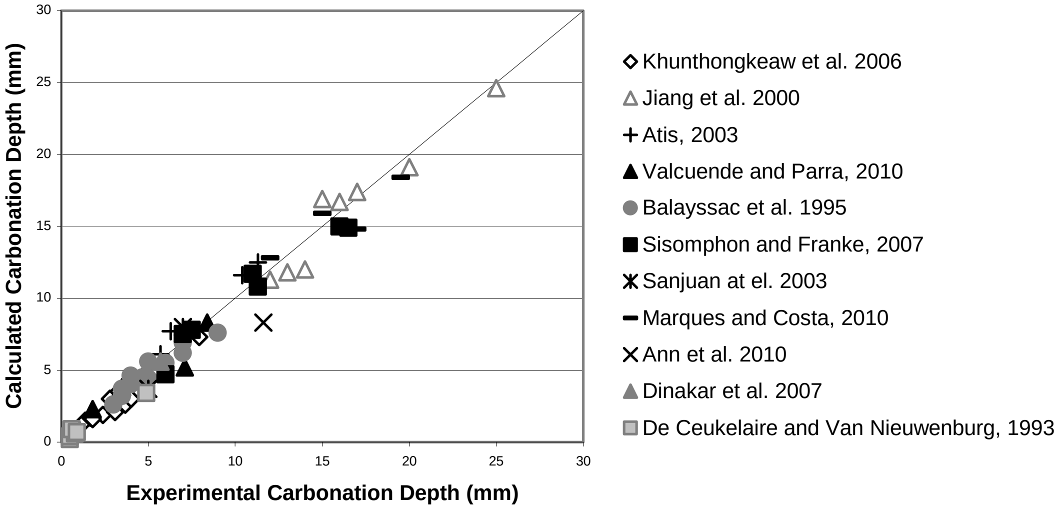

Figure 4. Comparison of calculated to experimental carbonation depth values

From the characteristic data given in Table 2 it can be seen that the model yields very accurate predictions for a range of both accelerated (up to 1 year) and natural exposure times (up to 18 years, where considering the experimental value of 11.62 mm with a standard deviation of 2.45, the 8.3 mm calculated is a very good approximation) and for different cement and concrete compositions. In Fig 5, just as a representative example, an excellent agreement between calculated and experimental values is observed, for a longer natural exposure time (up to 4.5 years) and for different w/c ratios.

Table 2. Characteristic Estimated Carbonation Depth Values

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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
Valcuente & Parra, 2010	CEM II/B-M	0.55	60.8	0.035	3.50	3.80	9 months
Valcuente & 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 *

* denotes accelerated exposure

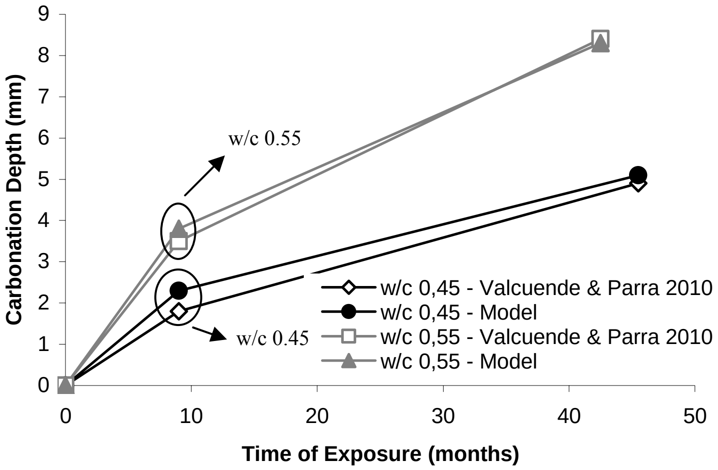

Figure 5. Calculated and experimental carbonation depth values for different w/c ratios of a CEM II/B-M type of cement.

4. CONCLUSIONS

The increasingly observed reduction of reinforced concrete structures service life, necessitates the need for a more robust durability approach implemented on the design stages of a project. Considering that on the European Standard for concrete [EN 206-1, 2000] durability is also defined through performance-related methods, based on proven predictive models, a significant step forward could be the development of appropriate software packages, according to the principles previously mentioned, for the estimation of concrete strength and service life. Such a prediction tool developed by Papadakis et al., for compressive strength and service life estimation, is briefly presented and validated in this study. A rather simple (yet accurate) equation for compressive strength prediction has been developed based on cement strength class. By using the concept of k-value (efficiency factor) of any active addition, the prediction formula is extended in the cases of incorporation of these supplementary cementing materials in concrete. By simulating the physicochemical processes in concrete in a quantative way and by taking into account deterioration models for carbonation and chloride exposures, developed by Papadakis et al, the concrete service life can be reliably predicted.

The validation for compressive strength and service life estimation for carbonation exposure, using a variety of experimental results from the literature and worksite specimens, for a wide range of w/c ratios, cement contents, type of cements and exposure conditions, illustrate a generally excellent agreement, proving thus the validity of the proposed method. It is hoped that the focus, the results and the proven soundness of the predictive tools presented in this study, will pave the way for the adaptation of valid software prediction models as a tool of paramount importance in achieving a soundproof level of durability on a reinforced concrete structure.

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