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Predictive modeling of concrete compressive strength based on cement strength class

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Abstract. In the current study, a method for concrete compressive strength prediction (based on cement strength class), incorporated in a software package developed by the authors for the estimation of concrete service life under harmful environments, is presented and validated. Prediction of concrete compressive strength, prior to real experimentation, can be a very useful tool for a first mix screening. Given the fact that lower limitations in strength have been set in standards, to attain a minimum of service life, a strength approach is a necessity. Furthermore, considering the number of theoretical attempts on strength predictions so far, it can be seen that although they lack widespread accepted validity, certain empirical expressions are still widely used. The method elaborated in this study, it offers a simple and accurate, compressive strength estimation, in very good agreement with experimental results. A modified version of the Feret's formula is used, since it contains only one adjustable parameter, predicted by knowing the cement strength class. The approach presented in this study can be applied on any cement type, including active additions (fly ash, silica fume) and age.

Keywords: cement; compressive strength; concrete; modeling; software; strength class

1. Introduction

Concrete compressive strength is by far one of the most significant properties of concrete, included in many experimental studies and historically being the first one that researchers attempted to estimate (Illston and Domone 2001, Neville 1995). Hardened concrete is classified with respect to its compressive strength (of 28 days), according to the relevant European Standard (EN 206-1 2000), in which it also mentioned that the characteristic strength of concrete, shall be equal or greater than the minimum characteristic compressive strength for the specified compressive strength class. Furthermore, in the Standard, certain lower limitations on strength are imposed as well, in order to attain a minimum of service life and to fulfill the minimum requirements of the concrete mixture appropriate for a specific exposure class. Hence, an approach based on strength prediction should be a part of any valid service life estimation.

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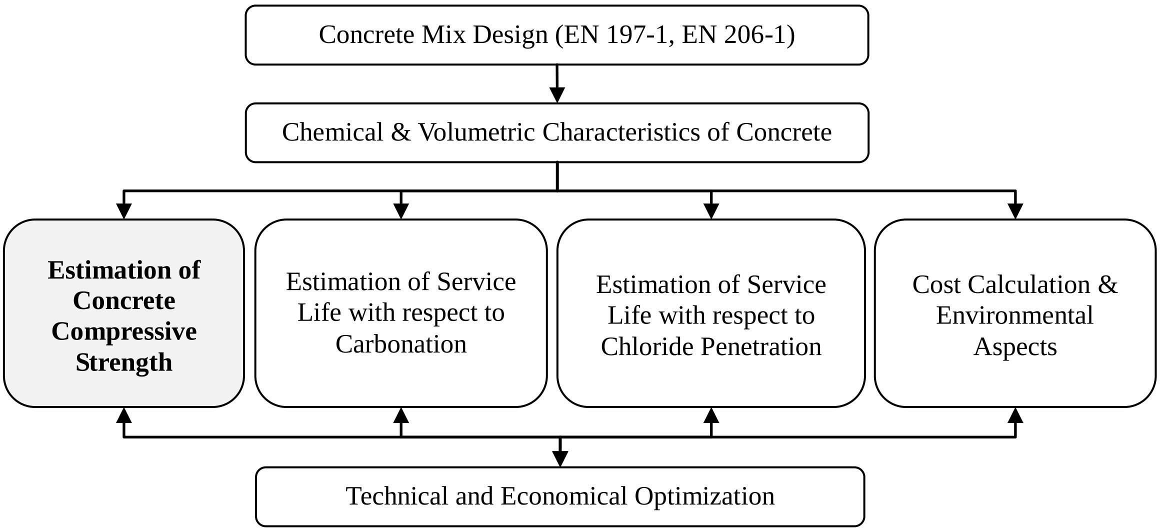

Fig. 1 Overview of calculation steps (tabs) of software for estimation of concrete service life and strength

In the following sections of this study, a method of concrete compressive strength prediction based on cement strength class is presented and validated. Such an approach is integrated on a software tool, previously published (Papadakis *et al.* 2007) based on proven predictive models (according to performance-related methods of EN 206 for assessing durability) developed and validated by the authors (Demis and Papadakis 2012, Papadakis *et al.* 1991, 2007, 2011), for the estimation of concrete service life when designing for durability under harsh environments. Its structure is illustrated in Fig. 1.

A quick description of the individual (and also interlinked) main calculation steps (tabs), of the software package can be defined as follows. Upon 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 (Fig. 2), which as it is elaborated in the following section it introduces 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 (carbonation and chloride penetration). Principles of chemical and material engineering have been applied to simulate the physicochemical processes.

In general, prediction of concrete compressive strength as a function of its compositional parameters can be a very useful aspect for a first mix screening, prior to real experimentation. Research has shown (Bensted 1983, Brunauer and Copeland 1964, Frigione 1983, Lea 1970, Neville 1995, Van Breugel 1991) that on a CEM I type of cement, according to EN 197-1 (2000), the main strength components in hydrated paste are calcium silicates (C_3S and C_2S) due to production of calcium-silicate-hydrate (C-S-H). However, in the early stages of hydration (0-7 days) the alumino-ferrite phases, especially in the presence of gypsum, make a significant contribution to the total strength. At an advanced (>28 days) or "complete" hydration level, the strength that the C_3A or C_4AF phase (in the presence of gypsum) can contribute is only 10% of the

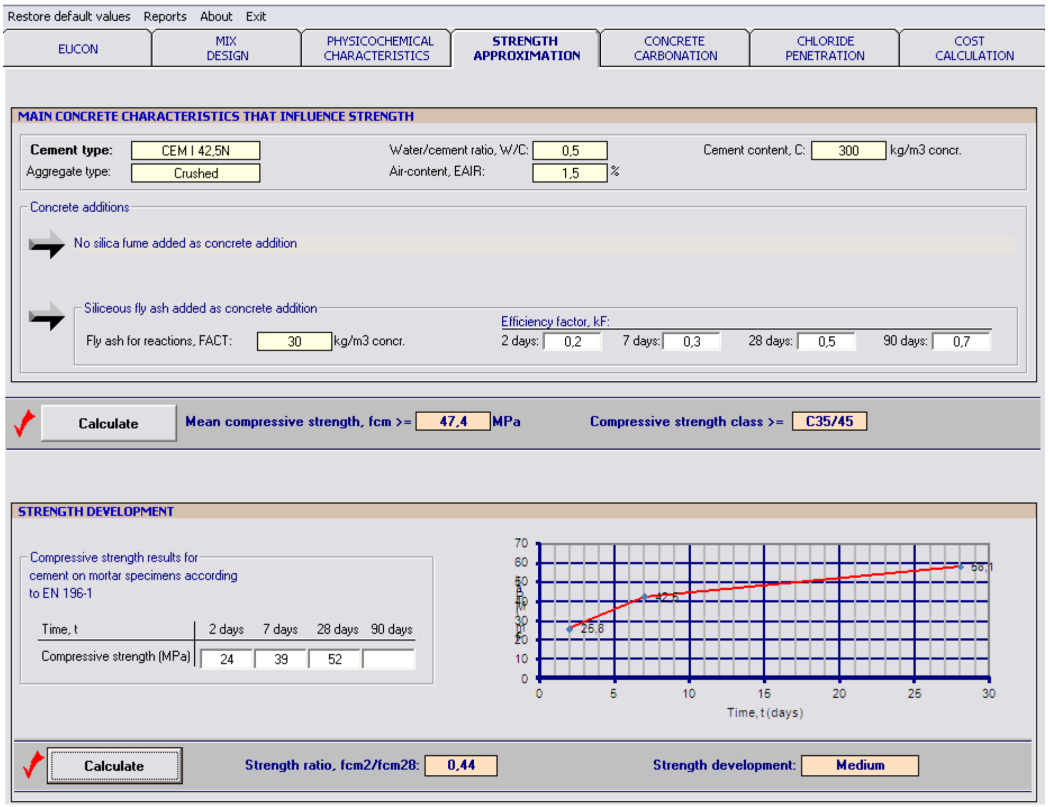

Fig. 2 Overview of the concrete compressive strength estimation section of the software package

strength of the C_3S or C_2S phase. As these phases (C_3A and C_4AF) are present at a low concentration in cement, it is principally the product of C_3S and C_2S (i.e., C-S-H), that is correlated with the total strength of the hydrated cement. Bearing all of the above in mind, and considering that concrete porosity, especially in the transition zone between cement paste and aggregate surface, is a crucial factor influencing the concrete compressive strength, a strength prediction approach could possibly be developed, based on the fundamental chemical and volumetric characteristics of concrete (C-S-H content, porosity and pore size distribution).

2. Analytical estimation of concrete compressive strength

Overall, a reliable prediction of concrete strength based on the contribution of each individual compound or characteristic can be a very difficult and challenging process, since their contribution is not just additive and has been found to depend on age and curing conditions (Neville 1995, Van Breugel 1991). Furthermore, a generally applicable Equation of strength prediction is not possible due to, interaction between the various compounds, including additions and supplementary cementing materials (SCM), the influence of alkalis and gypsum, the influence of the particle size distribution of cement, the influence of particle size distribution and shape of aggregates, etc. Many attempts have been made to generate strength prediction of cement paste, mortar and concrete, without however a general accepted validity. On the other hand, many empirical expressions have been proposed for strength prediction, presenting the most crucial dependences of strength from concrete compositional parameters and calculating the adjustable parameters from experiments (Aitcin and Neville 2003, Brunauer and Copeland 1964, De Larrard 1995, Jennings 1983, Lea 1970, Neville 1995, Pann *et al.* 2003, Popovics 1998, Van Breugel 1991). Some of them use rather conventional ways for this approximation, while others more developed ones are based on maturity methods (Viviani *et al.* 2008), or on probabilistic neural network methods (Kim *et al.* 2009).

Highly sophisticated attempts, including utilization of hybrid search algorithms (Mousavi *et al.* 2010) that combine genetic programming with orthogonal least squares (GP/OLS), or utilization of ultrasonic pulse velocity (UPV), one of the most widely used Non-Destructive Testing methods and artificial neural networks (ANN) (Al-Salloum *et al.* 2012, Bilgehan and Turgut 2010) have shown promising results in predicting concrete compressive strength in both normal and high strength concrete. Relationships between concrete compressive strength, UPV, density values (Bilgehan and Turgut 2010) and other concrete constituents (Al-Salloum *et al.* 2012) showed that utilization of ANN or GP/OLS models can be applied with a low error margin on concrete strength prediction. However, even though these methods are very promising, emphasis should also be paid on developing a simpler deterministic model of accurate concrete compressive strength estimation, as it is further illustrated.

In all empirical expressions for concrete compressive strength prediction proposed, the water to cement ratio (*W/C*) turns out to be the most important parameter. The first formulation of the relation of strength to the concrete constituents was made by Feret (Aitcin and Neville 2003, Illston and Domone 2001)

$$f_c = \frac{b\left(\frac{C}{d_c}\right)^2}{\left(\frac{C}{d_c} + \frac{W}{d_w} + \varepsilon_{air}\right)^2}, \quad \text{or} \quad f_c = \frac{b}{\left(1 + \frac{W}{C} \cdot \frac{d_c}{d_w} + \varepsilon_{air}\frac{d_c}{C}\right)^2} \tag{1}$$

where f_c is the mean concrete compressive strength (MPa), b is a parameter adjustable from experimental results, C is the cement content in concrete (kg/m^3 concrete), W is the water content in concrete (kg/m^3 concrete), d_C is the density of cement (kg/m^3), d_W is the density of water (kg/m^3) and ε_{air} is the air content in concrete.

Another well recognized relationship was introduced by Abrams (Aitcin and Neville 2003, Illston and Domone 2001)

$$f_c = \left(\frac{b_1}{b_2}\right)^{W/C} \tag{2}$$

where b_1, b_2 are adjustable parameters depending on the cement type, curing and age of test, and *w/c* is the water cement ratio.

Also, an additional empirical Equation is that induced by Bolomey (Kasperkiewicz 1994, Papadakis 1999, Papadakis and Tsimas 2002, Papadakis *et al.* 2002)

$$f_c = p_1\left(\frac{1}{W/C} - p_2\right) \tag{3}$$

where p_1 is a strength factor depending on cement type, aggregate type and air content (MPa) and p_2 is a time factor depending mainly on time, type of curing, and early strength class (cement fineness).

2.1 Concrete strength approximation using cement's strength class

All of the above mentioned Equations require experimental results for the calculation and adjustment of the parameters involved. In the lack of the latter, the information from the cement strength class (denoted herein as S_c) may be used to estimate a safe lower limit for concrete strength and thus to approach the corresponding value of compressive strength class. In the European Standard for cement (CEN EN 196-1 2000) a compressive strength test for cement on mortar specimens of fixed composition, is prescribed through which the cement strength class is defined. Specimens (40 mm equivalent cubes) made with a "CEN standard sand", natural, siliceous, and rounded in shape, with *W/C* and sand/cement ratios of 0.5 and 3 respectively, are cured in water, at 20^{o}C, until testing at 2, 7 and 28 days. However, when strength results from mortars are compared with ones from concretes, of the same *W/C* ratio, a significant difference is observed. Concrete strength is higher than the mortar strength, mostly due to the greater amount of entrapped air in mortar (Neville 1995). Using for example all the above information to Feret's formula (w/c=0.5, $d_C/d_W \approx 3.15$, $\varepsilon_{air} \approx 0.035$, $d_C \approx 3150$ kg/m^3, $C \approx 490$ kg/m^3), a lower value for parameter b can be estimated

$$f_c = \frac{b}{\left(1 + \frac{W}{C}\cdot\frac{d_c}{d_w} + \varepsilon_{air}\frac{d_c}{C}\right)^2} \geq S_c, \qquad \text{i.e.,} \quad b \geq 7.84\, S_c \tag{4}$$

where S_c is the standard strength class (at 28 days) of cement (MPa)

Using Eq. (4), the minimum compressive strength class of concrete (at 28 days) can be estimated, at other values of *W/C*, *C*, or ε_{air}, as

$$f_c \geq \frac{7.84\cdot S_c}{\left(1 + \frac{W}{C}\cdot\frac{d_c}{d_w} + \varepsilon_{air}\frac{d_c}{C}\right)^2} \tag{5}$$

If rounded aggregates are used, the above estimation has to decreased (Illston and Domone 2001) by a factor of 13%. On the other hand, if a strength result from the above mortar specimens is known, at another age (2, 7, or 90 days), it could be used in Eq. (5), 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.

Several other empirical expressions can be used as above, i.e., Abrams' (Eq. (2)) or Bolomey's (Eq. (3)). However, Feret's formula permits a rather safer approximation, since it contains only one adjustable parameter, compared to other models. Furthermore, the effect of air content is also incorporated, estimating that 1% variation in air content results in a variation of about 4.5% of the compressive strength, also according to other experimental studies (Aitcin and Lessard 1994). Since Feret's formula was extracted from mixes of high *W/C* ratios, at lower *W/C* mixes another exponent (than 2.0) may be used in Eq. (1). In any case, this approach is just a first approximation, valuable for the initial test proportioning (a detailed experimental verification is required). It has also to be emphasized that the above mentioned approach can be applied on any cement type, but it is valid only to concrete without any active additions, such as fly ash or silica fume (presented in the next section).

2.2 Strength approximation using SCM efficiency factor

When in a concrete mix, made with CEM I type of cement, a Type II addition is used (silica fume and/or fly ash), the pozzolanic action of the addition should be taken into consideration, since it produces strength components. In a previous publication (Papadakis 1999), a simplified scheme describing the activity of supplementary cementing materials (SCM) in terms of chemical reactions was proposed, yielding quantitative expressions for the estimation of the final chemical and volumetric composition of such SCM-concretes. A practical approach of the effect of SCM on the strength of Portland cement systems and on their resistance against carbonation and chloride penetration can be achieved, using the concept of the SCM efficiency factor (it is assumed that when active additions are used in concrete, a CEM I type of cement is strictly used).

The efficiency factor (or *k*-value) is defined as the part of the SCM that can be considered to be equivalent to Portland cement (CEM I), providing the same concrete properties (k=1 for Portland cement). The quantity of the SCM in the concrete mix can be multiplied by the *k*-value to estimate the equivalent cement content, which can then be added to the cement content for the determination of the water-to-cement ratio and the minimum required cement content. The compressive strength was used so far, as the property for the estimation of *k*-values (CEN EN 206-1 2000, Papadakis and Tsimas 2002, Papadakis *et al.* 2002). Knowing the *k*-values, any mix design process becomes easier and more accurate.

In the case of SCM-concrete, the following expression for compressive strength can be used, by utilizing the concept of *k*-value in Eq. (5)

$$f_c \geq \frac{7.84 \cdot S_c}{\left(1 + \frac{W}{C + k_F \cdot F_{ACT} + k_S \cdot S_{ACT}} \cdot \frac{d_c}{d_w} + \varepsilon_{air} \cdot \frac{d_c}{C + k_F \cdot F_{ACT} + k_S \cdot S_{ACT}}\right)^2} \tag{6}$$

where F_{ACT} is the active content of fly ash as concrete addition (kg/m^3), S_{ACT} is the active contents of silica fume as concrete addition (kg/m^3), k_F is the efficiency factor of fly ash and k_S is the efficiency factor of silica fume.

The above mentioned active contents have been calculated and presented in other publications (Badogiannis *et al.* 2004, Papadakis and Tsimas 2002, Papadakis *et al.* 2002). Using Eq. (6), and a large number of experimental results, the *k*-values for various SCM are calculated (Table 1).

For siliceous fly ashes, a *k*-value of 0.5 was calculated (Table 1), for 28 days' strength (Papadakis 1999). These very low calcium fly ashes are very common in the vast majority of EU countries, where similar *k*-values (0.3-0.5) are proposed (EN 206-1 2000). However, as time proceeds, higher *k*-values are calculated (Table 1) for the previously mentioned fly ashes, approaching those of high-calcium fly ashes (0.7 for 91 days and 1.1 for 1 year) (Papadakis 1999).

In the case of calcareous fly ashes (as well for blast furnace slag and burnt shale), the *k*-values are around 1.0, at early ages, and then higher, as time proceeds. Hence, up to a certain level (Papadakis 1999), these specific pulverized fly ashes can substitute, equivalently, for Portland cement.

Natural SCMs exhibit much lower efficiency factors (about 0.3-0.4 for natural pozzolana). This is correlated with their low level of active silica content. In the case of an artificial pozzolan of low reactivity, very low *k*-values of 0-0.1 were calculated, proving that the lack of active silica, due to slowly-cooled production, plays a dominant role in pozzolanic activity. However, certain ultra fine artificial pozzolans as metakaolin (and silica fume) exhibited significant higher strengths, resulting at higher *k*-values (up to 3 at 28 days and onwards (Badogiannis *et al.* 2004)). As metakaolin was treated at high temperatures, almost all silica was converted into amorphous and thus reactive. This behavior is similar to that of silica fume, where higher *k*-values were also calculated, at 28 days (Papadakis 1999).

According to CEN EN 206-1 (2000), type II additions may be taken into account in concrete composition, with respect to the cement content and the *W/C* ratio, if their suitability is established. The suitability of the *k*-value concept is established for siliceous fly ash and silica fume. If other concepts, e.g. the equivalent concrete performance concept, modifications on the rules of the *k*-value concept, higher *k*-values, other additions or combinations of additions are to be used, their suitability should also be established. Establishment of suitability may result from either a European Technical Approach or from a relevant national standard or from a provision valid in the place of the use of concrete.

The CEN EN 206-1 (2000) permits the *k*-value concept to be taken into account in replacing the *W/C* ratio with $W/(C + k \cdot \text{addition})$ ratio and in the minimum cement content requirement.

The actual value of *k* depends on the specific addition. The standard, accepts only siliceous fly ash as type II addition in concrete. The maximum amount of siliceous fly ash to be taken into account for the *k*-value concept shall meet the requirement, Fly ash / cement ≤ 0.33 by mass. The *k*-values (k_F) permitted for siliceous fly ash addition in concrete containing cement type CEM I are 0.2 and 0.4 for CEM I 32.5 and CEM I 42.5 respectively.

Table 1 Efficiency factors (*k*-values) for supplementary cementing materials (Papadakis 1999, Papadakis and Tsimas 2002, Papadakis *et al.* 2002, Badogiannis *et al.* 2004)

Cementitious/ pozzolanic materials*	Strength (2 days)	Strength (7 days)	Strength (28 days)	Strength (90 days)
Portland clinker	1.0	1.0	1.0	1.0
Silica fume	1.0	2.0	3.0	2.4
Pozzolana (natural)	0.4	0.3	0.3	0.3
Metakaolin	1.0	1.8	3.0	3.0
Siliceous fly ash	0.2	0.3	0.5	0.7
Calcareous fly ash	1.1	1.1	1.2	1.0

* All these SCM (except silica fume and metakaolin) were ground prior to use up to a fineness of 400±20 m^2/kg according to Blaine's test. Silica fume and metakaolin are superfine materials from production (fineness approximately around 10,000 – 20,000 m^2/kg, measured using the N_2 BET method).

In the case of silica fume, its maximum amount to be taken into account for the *k*-value concept shall meet the requirement, Silica fume / cement ≤ 0.11 by mass. The *k*-values (k_S) permitted for concrete containing cement type CEM I for silica fume addition are, 2 for specified $W/C \leq 0.45$ and 2 for specified $W/C > 0.45$ (except exp. classes XC and XF, where $k = 1$).

In general, an agreement was observed between EN 206 recommendations and the approach presented in this work. For example, in the current study only the active parts of fly ash and silica fume were considered (typically for siliceous fly ash: $F_{ACT} = 0.21C$, for calcareous fly ash: $F_{ACT} = 0.48C$, and for silica fume: $S_{ACT} = 0.14C$, maximum values; when these materials are used alone). When both silica fume and fly ash are used, lower active parts were estimated (Papadakis and Tsimas 2002, Papadakis *et al.* 2002). On the other hand, for the case of siliceous fly ash and silica fume, similar *k*-values are proposed by the EN 206.

The present work is more general from EN 206, giving the dependence of *k*-values on time, including the case of a combined use of both silica fume and fly ash and introducing also the use of calcareous fly ash as (a future) concrete addition. However, the EN 206 recommendations have to be applied officially without any alteration; the scope of the present work is just on strength prediction and thus it can be used for assistance on initial proportioning.

3. Comparison of predictions and experimental results (experimental verification)

A two step verification process was followed, based on data collected from ready-mix cement plants and on literature-based data. Characteristic examples of these sets of data, as well as their overall comparison with the compressive strength values, calculated using the predictive models developed, are presented in this section.

3.1 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). Crushed aggregates of 31.5 mm maximum grain size were used, whereas a mean air-content equal to 1.2%, as representative in the most cases, was assumed. Characteristic examples from these sets of data are given in Tables 2 and 3.

As shown in Fig. 3, an excellent agreement was observed between strength measurements and predictions, based on the previously described Eq. (5), for the CEM I / 42.5 cement type (according to CEN EN 197-1 (2000)). The cement strength class for these specimens (i.e., the S_c parameter of Eq. (5)) was 42.5.

As far as the CEM II/32.5 type of specimens are concerned (Fig. 4), a first quick observation can be translated as a slight underestimation, especially for the range of *w/c* ratios from 0.3 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. In essence this is a common practice of cement factories in order to satisfy statistical conformity criteria (and strength requirements) of EN 197-1 (2000). Bearing the above in mind, 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

Table 2 Characteristic examples of CEM I data collected from ready-mix cement plants

Sample	*C* (kg/m^3)	*w/c*	$f_{c,\,exp}$ (MPa)	$f_{c,\,calc}$ (MPa)
1	500.0	0.28	87.3	86.9
2	400.0	0.48	54.4	49.0
3	420.0	0.48	54.2	49.2
4	350.0	0.55	49.0	41.3
5	373.5	0.55	37.0	41.5
6	320.0	0.61	40.5	36.1
7	300.0	0.63	37.7	34.4
8	300.0	0.63	34.7	34.4
9	300.0	0.63	37.0	34.4
10	302.0	0.65	33.7	31.1

* *C* is the cement content, *w/c* the water cement ratio, $f_{c,exp}$ and $f_{c,cacl}$ the experimental and calculated concrete compressive strengths (respectively).

Table 3 Characteristic examples of CEM II/B-M data collected from ready-mix ready-mix cement plans

Sample	*C* (kg/m^3)	*w/c*	$f_{c,\,exp}$ (MPa)	$f_{c,\,calc}$ (MPa)	actual $f_{c,\,calc}$ (MPa)
1	530	0.42	52.6	44.4	53.3
2	465	0.45	42.1	40.8	49.0
3	430	0.48	45.6	37.7	45.2
4	429	0.49	43.3	36.8	44.2
5	426	0.50	42.5	35.9	43.1
6	406	0.51	40.9	35.0	41.9
7	406	0.53	43.0	33.4	40.1
8	360	0.56	36.4	31.0	37.1
9	371	0.56	33.9	31.0	37.2
10	360	0.58	37.0	29.6	35.6

* *actual* $f_{c,cacl}$ is the calculated concrete compressive strength, based on mortar strength

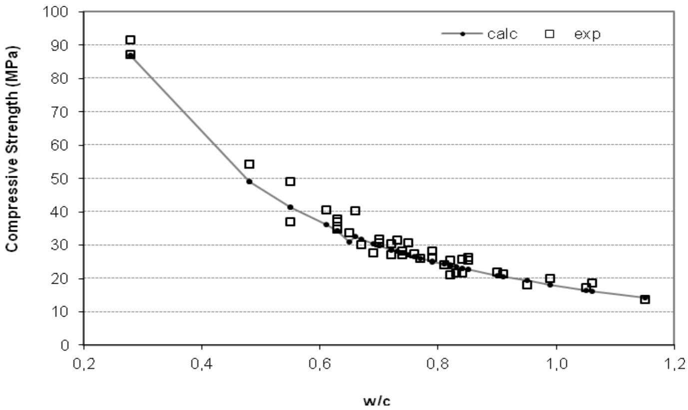

Fig. 3 Comparison between predictions of the 28 days-compressive strength using Eq. (5) and experimental measurements of CEM I / 42.5 type of cement

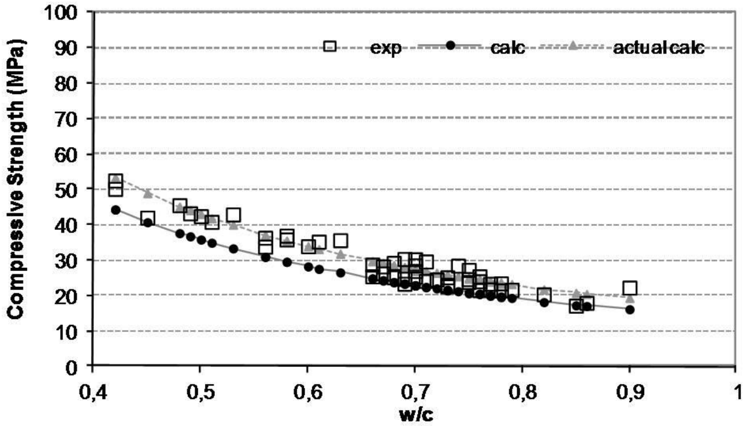

Fig. 4 Comparison between predictions of the 28 days-compressive strength using Eq. (5) and experimental measurements of CEM II / 32.5 type of cement

Table 4 Mix design and concrete properties of CEM I type of cements

Reference	S_c	W (kg/m^3)	C (kg/m^3)	w/c	ε_{air} (%)	$f_{c,\,exp}$ (MPa)	$f_{c,\,calc}$ (MPa)
Bilek (2003)	42.5 R	125	390	0.32	1.99	72.0	70.8
Liu (2010)	42.5 N	178	539	0.33	2.10	73.3	71.3
Szilagyi *et al.* (2007)	52.5 R	199	510	0.39	2.30	70.5	73.2
Kockjal and Turker (2007)	42.5 N	153	340	0.45	1.80	50.9	49.9
	42.5 N	185	260	0.71	1.80	27.0	27.9
Antiohos and Tsimas (2003)	42.5 N	165	350	0.47	1.50	50.2	48.7
	42.5 N	203	350	0.58	1.50	32.8	38.0
Jasiczak and Szymanski (2005)	32.5 R	175	350	0.50	2.30	35.9	32.9

Where, S_c is the standard cement strength class and ε_{air} the air content of concrete

re-calculated to approach in a more accurate way the compressive strength of concrete at 28 days(actual $f_{c,\,calc}$ in Table 3). 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. 4).

3.2 Comparison with literature-based data

At the second verification stage of the compressive strength predictive model, validation using data obtained through-out the literature was achieved. A wide range of experimental data were collected concerning CEM I type of cements, CEM I with Type II additives (silica fume, fly ash), as well as 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

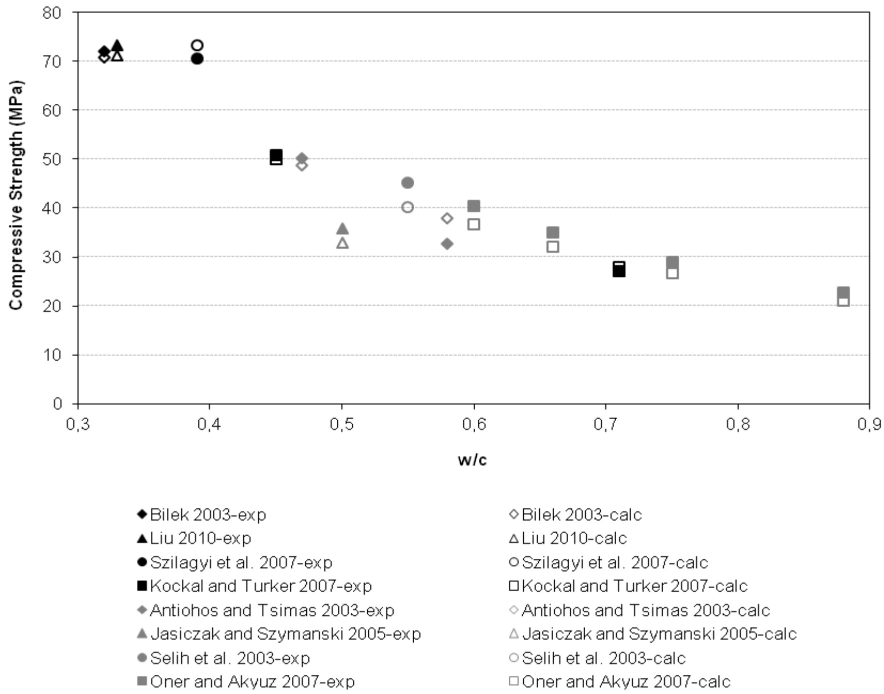

Fig. 5 Comparison of experimental with estimated values of concrete compressive strength for CEM I type of cements

Table 5 Mix design and concrete properties of CEM I with Type II additives type of cements

Reference	S_c	W (kg/m^3)	C (kg/m^3)	F (kg/m^3)	S (kg/m^3)	w/c	ε_{air} (%)	$f_{c\ exp}$ (MPa)	$f_{c,calc}$ (MPa)
Liu (2010)	42.5 N	176	437	80	-	0.40	2.1	69.7	66.5
	42.5 N	173	333	162	-	0.52	2.1	58.5	50.9
	42.5 N	170	225	247	-	0.76	2.1	37.2	31.2
Antiohos and Tsimas (2003)	42.5 N	203	245	105	-	0.83	1.5	31.4	30.4
Barbhuiya *et al.* (2009)	42.5 N	202	404	173	-	0.50	2.1	50.0	49.2
	42.5 N	195	333	299	16.7	0.60	2.1	50.0	43.8

where F and S are the fly ash and silica fume contents (respectively)

air content values of aggregate sizes of 31.5 mm, 16 mm and 8 mm, as 1.5%, 2.3% and 3.5% respectively. As it will be seen, a wide range of w/c ratios was covered (from 0.3 to 0.9).

The results are presented in Figs. 5-7 and the mix design of the data obtained from the literature, are also given in Tables 4-6. The estimated concrete compressive strength values of CEM I type of cements are in very good agreement with the experimental ones (Fig. 5, Table 4). A mean variation of 6.6% was observed.

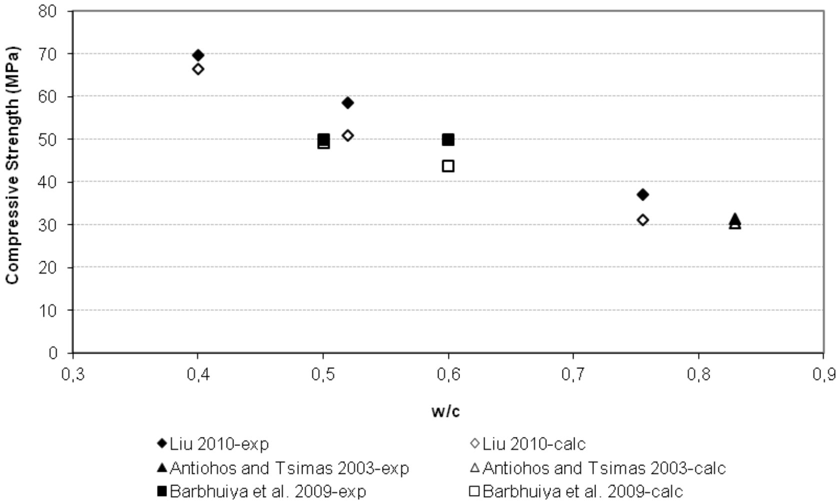

Fig. 6 Comparison of experimental with estimated values of concrete compressive strength for CEM I type of cement incorporating Type II additives

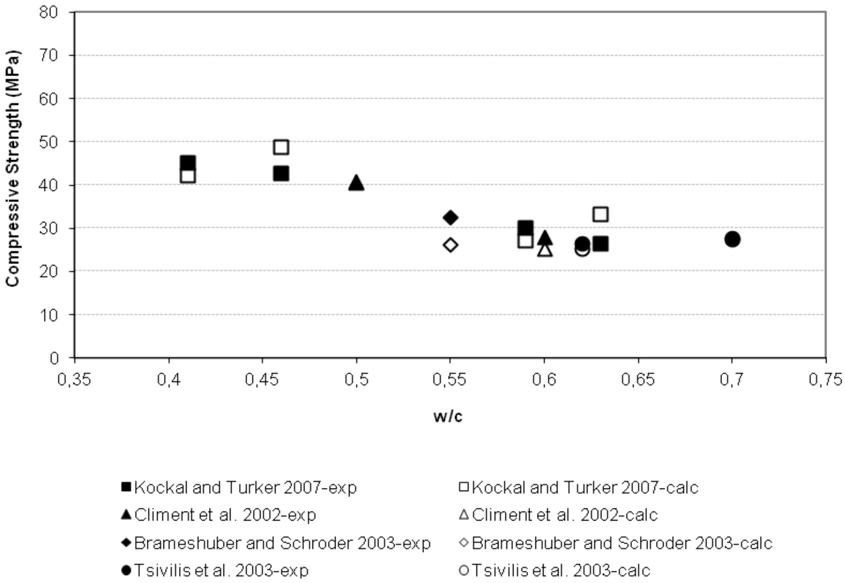

Fig. 7 Comparison of experimental with estimated values of concrete compressive strength for CEM II, III type of cements

An overall good agreement was also noted when Type II additions (fly ash, silica fume) were used (Fig. 6, Table 5).

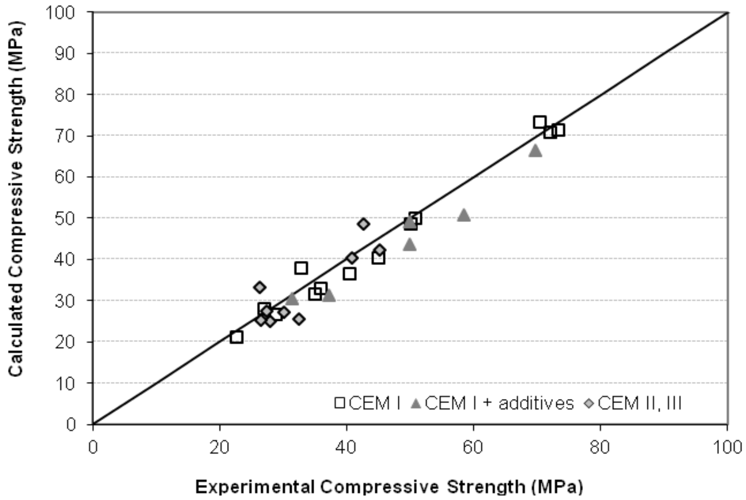

Fig. 8 Comparison of experimental with calculates values of concrete compressive strength for every type of cement used

Table 6 Mix design and concrete properties of CEM II, III type of cements

Reference	Type	S_c	W (kg/m^3)	C (kg/m^3)	w/c	ε_{air} (%)	$f_{c',exp}$ (MPa)	$f_{c',calc}$ (MPa)
Kockal and Turker 2007	CEM II/B-M	32.5 R	139	340	0.41	1.80	45.2	42.2
	CEM II/A-M	42.5 N	156	340	0.46	1.80	42.6	48.7
	CEM II/B-M	32.5 R	165	280	0.59	1.80	30.1	27.2
	CEM II/A-M	42.5 N	195	310	0.63	1.80	26.4	33.2
Climent 2002	CEM II/A-L	42.5 R	175	350	0.5	3.33	40.8	40.4
	CEM II/A-L	32.5 R	210	350	0.6	3.33	27.9	25.1
Brameshuber and Schroder 2003	CEM III/A	32.5 R	165	300	0.55	4.00	32.5	25.6
Tsivilis *et al.* 2003	CEM II/B-L	32.5 R	205	333	0.62	2.30	26.5	25.3
	CEM II/A-L	42.5 R	189	270	0.70	2.30	27.4	27.6

In the case of other types of cement (CEM II, III), where results from different standard cement strength classes where used (32.5, 42.5), again, the estimated concrete compressive strength values are in good agreement with the experimental ones (Fig. 7, Table 6). In certain cases the difference, of the estimated to the experimental value of strength, noted is within the aims and scope of the predictive model in providing a safe lower limit of concrete compressive strength.

The overall comparison for every type of cement used between the estimated and the experimental data is presented in Fig. 8

It can be seen, that overall the new proposed method for estimation of the concrete compressive strength, based on cement strength class (S_c), offers an accurate approach on any type of cement used, incorporating or not Type II additives.

4. Conclusions

In the lack of experimental results the information from the cement strength class may be used to estimate a safe lower limit for concrete strength and thus to approach the corresponding value of compressive strength class. In the present paper, a simple and accurate Equation for compressive strength prediction (utilizing a modified version of Feret's formula) is presented, based on the cement strength class. The approach presented can be applied to estimate concrete strength at any age and for any cement type, provided that this cement type strength is known for that particular age. 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.

The predictions of the present approach were compared with strength measurements of worksite specimens and with results obtained from the literature (covering a wide range of cement types, *w/c* ratios, cement contents and additions of Type II additives), illustrating 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 compressive strength predictive model, presented in this study, will pave the way for the adaptation of this approach as a useful tool for a first compressive strength approximation (a safe lower bound), valuable on the initial test proportioning, before any detailed experimental verification.

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