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Uporaba koncepta k-vrednosti, koncepta enakovrednega obnašanja betona in koncepta enakovrednega obnašanja kombinacij

Use of k-value concept, equivalent concrete performance concept and equivalent performance of combinations concept

k-Wert-Ansatz, Prinzipien des Konzepts der gleichwertigen Betonleistungsfähigkeit und Konzept der gleichwertigen Leistungsfähigkeit von Kombinationen aus Zement und Zusatzstoff

Utilisation du concept de coefficient k, concept d'équivalence de performance et concept d'équivalence de performance en combinaison

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Use of k-value concept, equivalent concrete performance concept and equivalent performance of combinations concept

Utilisation du concept de coefficient k, concept d'équivalence de performance et concept d'équivalence de performance en combinaison

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Foreword

This document (CEN/TR 16639:2014) has been prepared by Technical Committee CEN/TC 104 “Concrete and related products”, the secretariat of which is held by DIN.

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0 Introduction

0.1 General

This report outlines the current understanding of the use and application of three concepts used within EN 206:2013 for Type II additions to concrete. These are the *k*-value concept, the Equivalent Concrete Performance Concept (ECPC) and Equivalent Performance of Combinations Concept (EPCC).

Within 5.2.5 of EN 206:2013 *k*-values are given for fly ash and silica fume and a recommended *k*-value for GGBS as well as general principles for the ECPC and the EPCC concepts. It is also stated in EN 206:2013 that modifications to the rules of application of the *k*-value concept are permitted if 'suitability is established'. As stated within EN 206:2013 the establishment of suitability should result from provisions valid in the place of use of the concrete. In order to further explain the three concepts and to give guidance to the regulation writers and users of these concepts, this report provides background information and an overview of these concepts and rules of application as used within Europe.

0.2 Task Group 5

CEN/TC 104/SC 1 created Task Group 5 (TG 5) "Use of Additions" and assigned them the task to update EN 206-1:2000, 5.2.5 as part of the revision of EN 206-1. Because of the publication of product standard EN 15167-1 for ground granulated blastfurnace slag (GGBS), TG 5 was also asked to include rules for GGBS. CEN/TC 104/SC 1 passed various resolutions instructing TG 5 that it should implement the EPCC and ECPC concepts and the existing *k*-value concept for use of additions at the concrete mixer.

The rules for the use of type II additions in concrete according to EN 206:2013 are given in 5.2.5 "Use of additions". For two additions, fly ash and silica fume, specific requirements for their use with *k*-values are given. In this prescriptive *k*-value concept for concrete mix design, the defined rules are on the safe side and cover all possible variations for the possible permutations of cement and addition. An alternative option is the use of ECPC and EPCC concepts. Their principles are described in EN 206:2013, 5.2.5.3 and 5.2.5.4 while examples for the assessment using these concepts are given in this CEN/TR. The rules for these performance concepts should also be safe and lead to a more efficient use of additions.

0.3 *k*-value concept

With respect to the *k*-value concept in EN 206:2013, it was agreed that for fly ash and silica fume prescriptive *k*-values and cement substitution rates will be given which are proven to be on the safe side. Although the *k*-value concept for GGBS is included in some national regulations (see /2/) only a recommended value is given in EN 206:2013 due to limited practical experience. In national provisions, however, modifications to the rules of the *k*-value concept may be applied where their suitability has been established, e.g. higher *k*-values, increased proportions of additions, other additions (including type I), combinations of additions and other cements than those normally permitted. In this report the derivation of the prescriptive *k*-value approach is explained. The report also describes how the *k*-value concept should be applied by users such as the concrete producers.

0.4 ECPC and EPCC

The equivalent performance concepts, ECPC and EPCC, for the use of additions may be applied where suitability has been established. In countries where ECPC and EPCC are applied, nearly always, GGBS as addition to concrete is used under these concepts. This report describes how the ECPC and EPCC are applied in some European countries.

1 Scope

This Technical Report provides more detailed information on the k-value concept principles of the equivalent concrete performance concept (ECPC) and the equivalent performance of combinations concept (EPCC) in accordance to EN 206:2013, 5.2.5.

2 *k*-value concept

2.1 *k*-values in EN 206:2013

The *k*-value concept has been established for a number of years in a number of countries and was therefore implemented in EN 206-1 for fly ash and silica fume. In CEN/TC 104/SC 1 report N 278 (June 1996) the background was given to the application of *k*-value concept with fly ash concrete [1]. Later this concept was also applied for concretes containing silica fume and in some member states *k*-values for concretes with ground granulated blastfurnace slag (GGBS) are given in national application documents.

In EN 206:2013 prescriptive *k*-values are given for fly ash and silica fume and a recommended one for GGBS. These *k*-values allow the use of these additions in concrete throughout Europe with a restricted range of cement types within the requirements of the standard without any further verification procedure, i.e. without further testing except for the normal quality control for the concrete. In a prescriptive concept for concrete mix designs, the defined rules shall be on the safe side and cover all possible combinations of materials and variations for the given addition.

The *k*-value concept is a prescriptive concept. It is based on the comparison of the durability performance (or strength as a proxy-criterion for durability where appropriate) of a reference concrete with cement “A” against a test concrete in which part of cement “A” is replaced by an addition as function of the water/cement ratio and the addition content. With the proof of durability indirectly the proof for the exposure classes is given.

The *k*-value concept permits type II additions to be taken into account:

— by replacing the term “water/cement ratio” with “water/(cement + *k* * addition) ratio” and;

— the amount of (cement + *k* * addition) shall not be less than the minimum cement content required for the relevant exposure class.

When part of Cement “A” is replaced by an addition, the limiting values that have to be applied are those that would apply for Cement “A”.

The rules of application of the *k*-value concept for fly ash conforming to EN 450-1, silica fume conforming to EN 13263-1 and ground granulated blast furnace slag conforming to EN 15167-1 together with cements of type CEM I and CEM II/A conforming to EN 197-1 are given in corresponding clauses in EN 206:2013.

Modifications to the rules of the *k*-value concept may be applied where their suitability has been established (e.g. higher *k*-values, increased proportions of additions, other additions (including type I), combinations of additions and other cements than permitted.

2.2 Use of *k*-values in the member states

The use of *k*-values for type II additions in concrete has developed differently across the European member states over years. Within the revision work of EN 206:2013 member states experience was compiled with a series of differing enquiries. In 2007 a “Survey of National requirements used in conjunction with EN 206-1:2000” was published [2]. For the use of additions this enquiry was focused to the regulations for different classes of LOI for fly ash, environmental compatibility and the use of *k*-values, especially for fly ash and silica fume. Five countries responded on the use of k-values for GGBS.

In March 2007, CEN/TC 104/WG 15 presented the results of a survey on the “Use of GGBS as a type II addition in concrete to EN 206-1”. Eight countries reported on the use of GGBS and it was found that GGBS is used as type II addition under the ECPC, EPCC and the *k*-value principles. However, the amount used based on the *k*-value concept is relatively limited and this experience is confined only to some Nordic countries [3].

Within the revision work of 5.2.5 “Use of additions” in EN 206:2013, TG 5 also prepared an enquiry on the use of *k*-values for additions [4] focusing the experience with the different additions, the *k*-values and the determination of these *k*-values. In total 12 countries answered to the enquiry. Three countries do not use the *k*-value concept as they are using existing performance concepts and one country does not use the *k*-value concept for GGBS resulting in nine countries with regulations for using GGBS with the *k*-value concept. The answers of the enquiry can be compiled as follows:

— The *k*-value was mostly established based on results of research work and experience.

— The compressive strength is mostly evaluated after 28 days on concrete samples (9 countries) or mortar (1 country).

— Where the *k*-value was determined the relationship between the compressive strength and water/cement-ratio of concrete samples was used.

— The type of cement and the maximum proportions of additions permitted vary widely in the National regulations, from the use with CEM I only to the use with all cements where the additions are also used in cement.

— Fly ash is used with more cement types than silica fume and GGBS using the k-value concept.

— *k*-values for fly ash vary from 0,2 to 0,8, those for silica fume from 1,0 to 2,0 and those for GGBS from 0,4 to 1,0.

— Where *k*-values had been determined the durability aspects had also been taken into account.

— Most of the countries have experience with *k*-value concept for fly ash and silica fume, only a few countries use the *k*-value concept for GGBS.

The single answers to the TG 5 enquiry are given at the end of this report.

2.3 Procedure for using the *k*-value concept

2.3.1 Principle of the *k*-value concept

Type II additions contribute to concrete properties by various mechanisms. Their influence on concrete properties depends on the characteristics of the individual material properties, on the age of concrete, on the ambient conditions (temperature, humidity) and various other parameters. To take into account these effects in the concrete mix design, the *k*-value method uses the relationship between the water/cement ratio and the strength of concrete. The concept was introduced by Iain A. Smith for the first time in 1967 for the design of fly ash concretes with fly ash amount up to 25 % [5] and has developed further on.

Based on the established concept of EN 206-1 and related Eurocodes the concrete mix design is based on the 28 days strength of concrete. Consequently the standardised prescriptive *k*-value for a concrete addition is related to this age. Nevertheless, when a *k*-value has to be defined, the durability of concretes shall be considered for the relevant exposure classes.

In concretes containing type II additions, the term “water/cement ratio” is replaced with “water/(cement + $k \cdot$ addition)” ratio. The factor k indicates the contribution of the addition in concrete compositions reaching the same strength like the reference concretes without addition.

When the condition of equal strength is assumed, Formula (1) is fulfilled for a specific *k*-value.

$$\omega_o = w_a / \left(c_a + k \cdot a \right) \qquad (1)$$

When these parameters have been determined for equal strength, k can be calculated;

$$k = \left(w_a / \omega_o - c_a \right) / a \qquad (2)$$

or if normalized to the cement content c_a of the concrete with addition

$$k = (\omega_a / \omega_o - 1)/(a / c_a) \quad (3)$$

where

ω_o is the water/cement ratio of reference concrete without addition;

w_a is the water content of the concrete with addition;

c_a is the cement content of the concrete with addition;

a is the addition content;

ω_a is the water/cement ratio of concrete with addition (w_a/c_a).

In prescriptive concrete design methods using the k-value concept, the constant k reflects the maximum value, which could be used to prove that the water/(cement + k · addition) ratio of the concrete does not exceed the maximum water/cement ratio as defined for the respective exposure class. It does not give any information about the effective performance of the used addition in the individual concrete mix.

When evaluating the results of different sets of concrete tests, various k-values could be determined as the efficiency of a concrete addition is dependent on a number of parameters (e.g. quality and properties of addition, amount of addition, cement type and properties, water/cement ratio, age, temperature, etc.). The calculation of k-values indicating the efficiency of a concrete addition is usually performed by the comparison of the water/cement ratio vs. compressive strength relationship for references concretes without addition and concretes with addition. For determining the efficiency of an addition, all concretes of a data set calculating k shall be made of the same cement.

2.3.2 Method of calculation

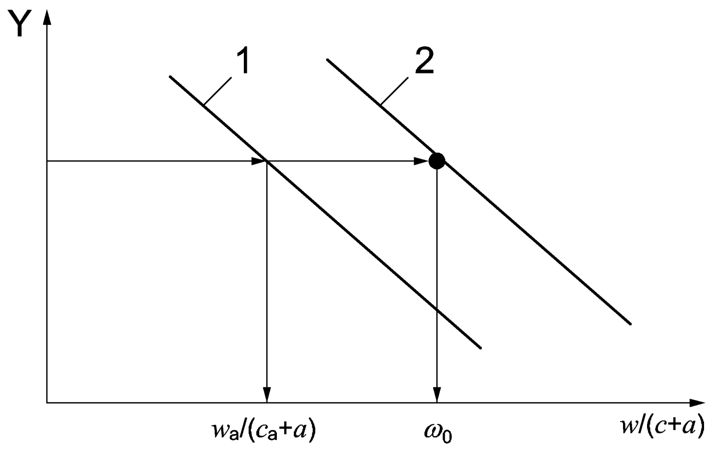
The method of calculating k-values is generally applicable to type II additions according to EN 206:2013. The k-value concept is based on the comparison of the performance of a reference concrete with cement “A” against a test concrete in which part of cement “A” is replaced by an addition as function of the water/cement ratio and the addition content.

The method described in the following, is based on the Smith method developed for fly ash in 1967 [5]. The basis for the calculation of k-value is based on the water/cement ratio vs. strength relationship of concretes with the same content of addition. The determination should preferably not be done on the results of single concretes mixes, but by a set of data. This allows a more precise determination of the water/cement ratio vs. strength relationship. To arithmetically describe that relationship, different empirical formulae could be used. Usually a linear relationship gives a good approximation of strength in restricted ranges of water/cement ratio

$$\text{Compressive strength} = a - b \cdot \text{water/cement ratio}$$

But also other nonlinear approaches (e.g. Abrams law [6, 7], could be used [8, 9]. The values of the factor “k” may also be given by technical feedback. E.g. in France, where the k-value concept is used for Type II and some type I addition (limestone and siliceous filler), the values are derived from the Bolomey method [10] and adjusted by experience.

Comparison of the different approaches shows that there might be slight differences in the calculated k-values, but the level of the results is similar. The variances in the measured compressive strength results have a much higher impact on the calculated values [11].



Key

1 addition with content a

2 reference

Y strength

Figure 1 — Principle of *k*-value determination (shown for *w* / (*c* + *a*))

Strength vs. water/cement – relationship of reference concrete:

$$f_o = A_o - B_o \cdot \omega_o$$

For a selected *c*/*a* ratio, the linear approximation can be assumed also for the correlation f_a versus w / (c + a) as shown by the following formula:

$$f_a = A_a - B_a \cdot (w/(c+a))$$

When a functional relationship between water/cement ratio and compressive strength based on test results has been determined for reference concretes without addition and concretes with a defined addition/cement ratio respectively both formulae are set to be equal;

$$f_{o\,\mathrm{(reference)}} = f_{a\,\mathrm{(addition)}}$$

$$f_o = f_a \;\Rightarrow\; A_o - B_o \cdot \omega_o = A_a - B_a \cdot w_a/(c+a) \qquad (4)$$

$$\omega_o = w_a / (c + k \cdot a) \;\Rightarrow\; w_a = \omega_o \cdot (c + k \cdot a) \qquad (5)$$

$$A_o - B_o \cdot \omega_o = A_a - B_a \cdot \omega_o \cdot (c + k \cdot a)/(c+a)$$ (5) substituted in (4)

or $A_o - B_o \cdot \omega_o = A_a - B_a \cdot \omega_o \cdot (1 + k \cdot a/c)/(1 + a/c)$

This follows the principle that the parameter *k* has to be determined on the basis of equal strength. Now, using Formula (3) and necessary arithmetic transformations, *k* can be determined. In this way of calculation, *k* will not be a single value but will be a parameter in functional dependence of the water/cement ratio of the reference concretes (ω_o).

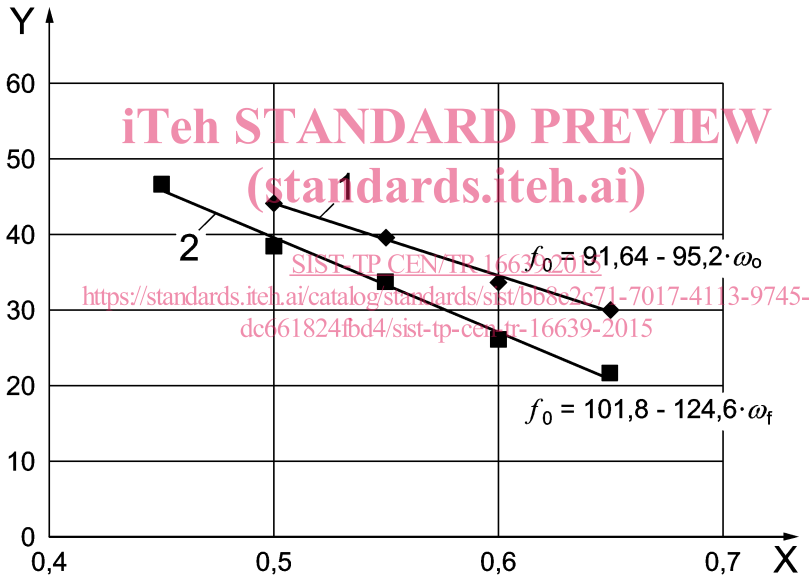
$$k = \frac{(A_a - A_o) \cdot (1 + a/c)}{B_a \cdot a/c} \cdot \frac{1}{\omega_o} + \left[\frac{B_o \cdot (1 + a/c)}{B_a} - 1\right] \cdot \frac{1}{a/c}$$

where

ω_o	water/cement ratio of reference concrete without addition
ω_a	water/cement ratio of concrete with addition (w_a/c_a)
w_a	water content of concrete with addition [kg/m³]
c_a	cement content of concrete with addition [kg/m³]
a	content of addition [kg/m³]
f_0, f_a	compressive strength of concretes [MPa]
A_0, A_a, B_0, B_a	empirical coefficients of the linear relations between water-cement ratio and strength of the reference concrete and the concrete with additions

2.3.3 Example for determination of k

For demonstrating the calculation of k, an example is used with concretes containing a fly ash content of 20 % by mass (related to cement plus fly ash). Figure 2 shows the relationship between water/(cement + fly ash) ratio and strength for the concretes with fly ash and the reference concretes without addition which have been used for the calculation.



Key

1 0 % fly ash

2 20 % fly ash

X water / (cement + fly ash) ratio

Y compressive strength at 28 days [MPa]

Figure 2 — Example for strength vs. water / (cement + fly ash) relationship

$$f_o = 91,64 - 95,20 \cdot \omega_o$$

$$f_f = 101,8 - 124,6 \cdot \text{water} / (\text{cement} + \text{fly ash})$$ with fly ash/cement = 0,25 (20 % fly ash)

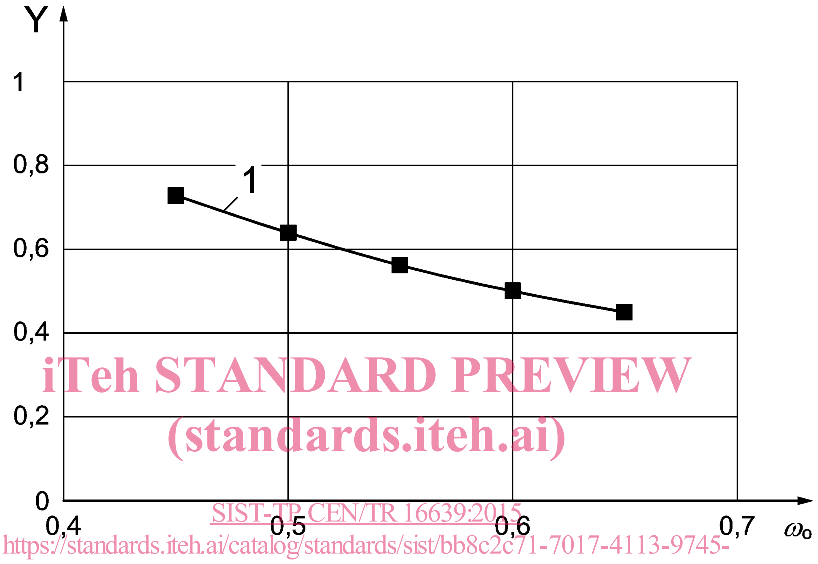
$$k = \frac{(101,8 - 91,64)\cdot(1+0,25)}{124,6\cdot 0,25}\cdot\frac{1}{\omega_o} + \left[\frac{95,20\cdot(1+0,25)}{124,6} - 1\right]\cdot\frac{1}{0,25}$$

$$\Rightarrow \underline{\underline{k = 0,408\cdot 1/\omega_o - 0,180}}$$

With this term, the k-value can be plotted as function of ω_o (see Figure 3).

For a given ω_o, k can be calculated, for example: ω_o = 0,50 k = 0,64

ω_o = 0,60 k = 0,50



Key

1 20 % fly ash

Y k-value at 28 days

Figure 3 — k-value plotted as function of water/cement ratio ω_o of reference concrete

Control

<u>Alternative 1</u>

Select a compressive strength, e.g. 35 MPa

$$f_o = A_o - B_o\cdot\omega_o = 35 = 91,64 - 95,20\cdot\omega_o$$

$$\Rightarrow \omega_o = (91,64 - 35)/95,20 = 0,595$$

$$f_f = A_f - B_f\cdot w/(c+f) = 35 = 101,8 - 124,6\cdot w/(c+f)$$

$$\Rightarrow w/(c+f) = (101,8 - 35)/124,6 = 0,536$$

$k = (\omega_f/\omega_o - 1)/(f/c)$ with $\omega_f = w/(c+f)\cdot(1+f/c)$ (see box in Figure 1)

$$\Rightarrow k = [(0,536(1+0,25)/0,595)-1]/0,25 = \underline{0,504}$$

Alternative 2

Select a w/c ratio, e.g. ω_o = 0,50

$$k(\omega_o = 0,50) = 0,408/0,50 - 0,180 = 0,636$$

$$f_o(\omega_o = 0,50) = 91,64 - 95,20 \cdot 0,50 = \underline{44,0\ \text{MPa}}$$

$$f_f = A_f - B_f \cdot \omega_o \cdot (1 + k \cdot f/c)/(1 + f/b)$$

$$= 101,8 - 124,6 \cdot 0,50 \cdot (1 + 0,636 \cdot 0,25)/(1 + 0,25) = \underline{44,0\ \text{MPa}}$$

NOTE The example origins from concretes with fly ash as addition therefore in the formulae the amount of fly ash is represented by the symbol f.

2.3.4 Further recommendations for the application of the *k*-value

For the application of the *k*-value concept the following recommendations should be considered:

— *k*-values should be calculated only for water/cement ratios in the range investigated (no extrapolation).

— Beside cement and addition all other concrete components have an effect on the strength of concrete. Therefore keep them constant.

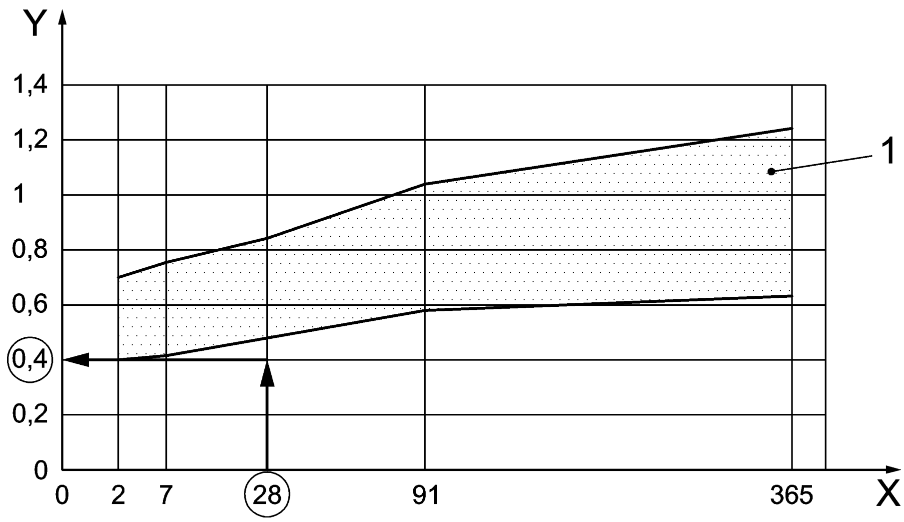
— If a constant workability is preferred, where necessary use a water reducing admixture (plasticiser) to ensure no excessive air is entrained.

— Ensure the variability in the determination of compressive strength is as low as possible because any scattering is magnified in the calculation of the *k*-value.

2.3.5 Example for establishing a general concept using the *k*-value concept

As an example the principles of the procedure of introducing the *k*-value for fly ash in the 1990s is demonstrated. The results of this approach were included in EN 206-1:2000.

The determination of the prescriptive *k*-value is performed in two steps. In the first step, *k*-values are calculated from concrete tests according to the procedure and recommendation reported above. In the concrete tests all relevant parameters (cement type, strength class, quality of addition, water/cement ratio, etc.) should be considered to allow the definition of a generally applicable prescriptive *k*-value. Figure 4 demonstrates the range of calculated *k*-values resulting from concrete strength tests using various combinations of different cements and a fly ash. The fly ash used for durability test as shown in Figures 5 and 6 is representative for a fly ash according to EN 450-1. It had been selected from pre-tests out of a range of more than 30 fly ashes. As shown in Figure 4 a prescriptive *k*-value of 0,4 was derived taking into account a certain safety margin [12].



Key

1 range of various cement and fly ash combinations

X age of concrete, [days]

Y k-value [–]

Fly ash content 20 % of total binder (f / c = 0.025)

Figure 4 — Determination of a prescriptive k-value from concrete test results [12]

In a second step, concretes with a composition using k = 0,4 or very similar k-value were produced.

In this case (Figures 5 and 6) the fly ash was taken into account by a k-value of 0,5 on the w / (c + $k \cdot f$) ratio.

Again all relevant parameters (cement type, strength class, quality of addition, water/cement ratio, etc.) were considered in the testing program. With these concretes it was proven that the critical durability requirements for a prescriptive concept (e.g. freeze thaw resistance and carbonation in that case) are fulfilled (Figures 5 and 6).

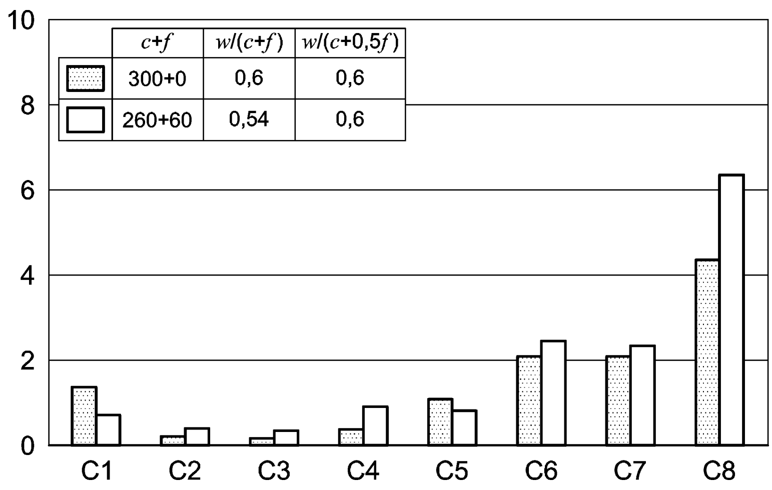


Figure 5 — Results from freeze–thaw testing verifying the suitability of a prescriptive k-value [12]