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Aspects concerning the applicability of the efficiency k-factor in the case of calcareous fly ash

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Abstract

Although there is much scepticism about the quantification of the influence of an addition on concrete performance by using a single k-factor, it seems that it serves as a convenient engineering tool for estimating the contribution of additions to the strength development. According to EN 206-1, Annex E, the efficiency k-factor could be used for siliceous fly ash, ground granulated blastfurnace slag (ggbs) and silica fume, for which relevant European Standards already exist. The k-factor values for fly ash range from 0.2 to 0.4. The literature on calcareous fly ash efficiency factor or factors is very limited and many questions should be answered before any efficiency consideration, such as: Which type of calcareous fly ash are we discussing? As it is known, this material is reactive and cannot be used as inert filler, mainly due to free lime and sulphate contents. Furthermore, fineness plays an important role on its performance in concrete and it possesses self-cementing properties and often increases the water demand of the concrete mixture in which it is added. In this paper, the whole problem relating to calcareous fly ash addition in concrete is addressed. Based on long term experience on the use of calcareous fly ash as a separate constituent of the binding system in the mixer, k-factors are given which are in the range of certain limits concerning chemical composition and fineness. By replacing up to 40% of cement with these calcareous fly ashes, the efficiency k-factor seems to be around unity. In addition, the performance of high volume of these fly ashes in concrete is given by presenting experimental results concerning strength development over quantity of fly ash and water to cementitious ratio.

Keywords: k-factor, calcareous fly ash

1 Introduction

The concept of k-factor or k-value as a tool for mix designing of concrete with additions has been introduced very early from the decade of 60’s, aiming at facilitating and providing safety to concrete designers when fly ashes are used as constituents of concrete (1, 2). The k-factor indicates how much of addition content contributes to the strength development of concrete. It has been adopted by EN 206-1 for silica fume, fly ash and ground granulated blast furnace slag (GGBS) for which there are European standards for their use in concrete (3). Therefore, k-value permitted for fly ash when is used in combination with CEM I42.5 is K=0.4. Other values may be used if properly justified in relation to their suitability and performance (4).

However, there is much skepticism about the efficiency of this prescriptive type factor since is based on 28-d strength and many other mechanisms influencing the performance of an addition in concrete mixtures are not taken into account, such as time-dependent effects due to pozzolanic character of addition, curing regime or exposure to chlorides and other aggressive environments (5). Therefore, by using durability properties other relative k-factors could be calculated (6). Calcareous fly ashes constitute a great part of the total fly ash output in Europe but they are not prescribed with European standards. As known, they often contain free lime and sulfates which may create expansion problems in concrete and volume instability. Since their behavior in concretes depends on lime, sulfate content as well as on fineness, it could be characterized as a reactive material which often increases the water demand of the concrete mixtures and consequently affects the compactability of concrete mixtures and finally the developed strength. Therefore, it should not be used as fine material having only filler effects except for the case it is added purposely as in the case of designing self-compacting concrete (6). In Europe, the use of calcareous fly ash as addition in conventional concrete is limited while it has been used for the construction of RCC dams or RCC pavements (7). There are also pilot applications such as shotcrete, self-compacting concrete and paving blocks in which calcareous fly ash was used by replacing cement at high percentage, above 50% by mass (8). The concept for mix design was based rather on equivalent concrete performance as has been introduced by EN 206, Annex 4. That means the concrete should present equivalent performance especially with respect to mechanical properties and durability when compared with a reference concrete in accordance with the requirements for the relevant exposure clauses (4). Under the pressure of the need for sustainability in construction and current economic recession, it seems logical to reconsider utilization of all available resources and make normative frame for its use in concrete. Towards this direction, a pre normative work on the applicability of k-value or other concept for mix design could be helpful. The presented experimental work is part of an extensive program about applicability of mix design concepts for concretes with calcareous fly ash.

2 THE APPLICATION OF K-FACTOR FOR CONCRETE MIX DESIGN WITH CALCAREOUS FLY ASH

At first, the applicability of the k-factor concept in concreting with calcareous fly ash as addition II is not allowed in Europe since there aren’t any standards on the use of this fly ash in concrete. However, if there are relevant National Standards on European Technical Approval, this k-value concept could be applied. In that case, the calcareous fly ash can be used only with the recommended cement types and meeting the requirements for a specific durability, by replacing a part of cement which will be calculated by the k-value. Since k-factor is a prescriptive type value, the calcareous fly ash may be used without any further verification apart normal quality control of concrete. This concept, although conservative, facilitates the manufacture of concrete with calcareous fly ash. On the contrary, following the equivalent concrete performance (HCPC) concept, the equivalent performance especially with respect to durability has always to be proven in comparison with reference concrete. Therefore, for everyday application of CF in conventional concrete the k-value concept seems more conventional. When calcareous fly ash is added to concrete, the water demand is often significantly increased. The free lime and sulfate content as well as calcium aluminate compounds and fineness seems to influence this extra requirement of water (9). This has an impact on workability and consequently to strength since less workable concrete mixtures are not well compacted. This fact is not properly taken into account in the k-value concept and implies the use of super plasticizers in high dosages, in particular when high percentages of calcareous fly ash are added. The reference concretes with and without calcareous fly ash should be designed and tested very carefully in order to estimate mathematically the k-value. Differences in chemical composition lead to different compressive strength versus water/cementious relationships. It seems that the total cementitious content and the percentage of cement replacement by fly ash affect the curves on which k-value calculation is based.

3 EXPERIMENTAL

In an effort to investigate the applicability of the k-value concept of calcareous fly ash as type II addition (EN 206) into conventional concrete, an extensive environmental program has set out, in the Laboratory of Building Materials AUTH, following methodology advised by CEN Technical Report about «Use of additions». The parameters taken into account were:

- Four different reference concretes with 280, 300, 350 and 370 kg/m^3 cement contents
- Two types of calcareous fly ash without any processing
- Various water/cementitious ratios; 0.40, 0.50, 0.60, 0.70
- 30% and 40% wt. cement replacement with fly ash

The parameters selected were, according to the existing experience, representative of the most common conventional concrete mixtures. One hundred mixtures have been manufactured for testing 28-d compressive strength by crushing six cubed for each measurement. Another hundred concrete mixtures have also been manufactured, in order to determine the performance of higher cement replacement rates by fly ash, such as 50%, 60%, 70% and 80% wt.

The physicochemical characteristics of material used for cementitious (cement and fly ash) content of the concrete mixtures are given in Table 1. Crashed limestone aggregates of 31.5 mm maximum size have been used and the granulometric curve of them is given in Fig.1. The concrete composition and compressive strength of mixtures for the series with 300Kg/m^3 cementitious material are shown indicatively in Table 2. Figures 2 to 5 show the first test results from the laboratory mixtures. Changes in workability have not been taken into account although they have been measured. With the addition of calcareous fly ashes, the slump value has been reduced (not for the same range for the two types of fly ashes F1, F2) and this was balanced by adding superplasticizers of polycarboxylic ether type from 0.5 up to 2% by mass of the total cementious content.

All cubic specimens were properly moist cured up to testing. The 28-d compressive strength versus water/cement or water/cementious material relationships have been plotted for four reference concretes with cement CEM I42.5 and with two concrete mixtures in which 40% of cement was replaced by calcareous fly ash F1 and F2. They are indicated in Fig2-5 after regression of equations $f_0=A_0-B_0 \cdot w_0$ and $f_\alpha=A_\alpha-B_\alpha \cdot (w/(c+\alpha))$ where:

w_0 : water/cement ratio of reference concrete without addition

α : content of addition in kg/m³

f_0 and f_α : compressive strength of concrete (MPa)

A_0, A_α, B_0 and B_α : empirical coefficients of the linear relation between water/cement ratio and strength of the reference concrete and the concrete with additions

The k-values calculated by using the equations resulting after arithmetic transformation are given in Table 3 for F1 and Table 4 for F2.

$$k = \frac{(Aa \quad A_0) \quad 1+\frac{a}{c}}{B_a \quad \frac{a}{c}} \quad \frac{1}{w_0} + \frac{B_0 \quad 1+\frac{a}{c}}{B_a} \quad 1 \quad \frac{c}{a}$$

When fly ash replace higher than 40% by mass of cement such as 50, 60, 70 and 80% that is found often in mass concrete, its contribution to strength development depends, for the same aggregate granulometry, on total cementitious content and water/cementitious ratio of the mixture. In Figs. 6-9 the obtained 28-d strength by replacing high volume of cement by F1 and F2 is shown. In this series of concrete mixtures, admixtures for modifying workability have not been used although it has been reduced and this fact has a negative effect on the strength. It seems that the 28-d compressive strength based on k-value takes values about 1 and it is different for each type of fly ash as well as for each reference concrete prescribed with a defined total cementitious content. In relation to water/cementitious ratio, the k-value is decreased as the ratio increases.

4 DISCUSSION AND CONCLUSIONS

Based on 28-d compressive strength results, it is concluded that for conventional concrete applications and for percentages of cement replacement up to 40% by mass, the k-value for the two raw fly ashes without any processing (F1 and F2) is around value 1. The reference curves (f_0-w_0 and f_α-w_α) differ accordingly to cement content. Extrapolation to percentages other than 40% such as 30 or 20% is not verified very well. The different in chemical composition two fly ashes showed different k-values. The higher in lime content fly ash, F1, indicated higher k-values. Of course, after following durability tests, this k-value may be reduced. According to references (10, 11) concrete incorporations calcareous fly ashes exhibited higher k-values for efficiency against chloride penetration (k=2-2.5) than those corresponding to 28-d strength (k=1).

Regarding the durability aspects which have to be tested to access k-value or equivalent concrete performance, the resistance to chloride penetration and carbonation, resistance to freezing-thawing, seawater and sulfate could be mentioned. It is noted that the first aspect in the case of calcareous fly ashes which should be checked is volume instability due to expansive constituents such as free lime and sulfate. The two raw fly ashes used in concrete mixtures in replacement of cement without any superplasticizers and, of course of lower workability, developed lower but considerable level of strengths (such as 80% of control mixture with 60% calcareous fly ash) for cement substitution. The workability measured in most of the rich in fly ash mixtures was S1 or around zero in low water/cementitious ratios.

In conclusion, a well-defined k-value could be used for the mix design of every day applications of conventional concrete up to 40% replacement of cement. When higher percentages are used for mass concrete production the equivalent concrete performance concept may be more flexible and cost effective.

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Table 1. Physicochemical characteristics of binders used in tested concretes

Chemical composition	CEM I42.5N	Fly ash F1	Fly ash F2
Na_2O (%)	0.57	1.00	1.16
K_2O (%)	1.08	0.53	1.06
CaO (%)	66.84	47.00	23.09
MgO (%)	3.91	3.20	2.47
Fe_2O_3 (%)	8.11	4.00	8.06
Al_2O_3 (%)	2.40	7.30	13.98
SiO_2 (%)	19.55	33.07	48.44
LOI (%)	91.00	3.75	1.74
SO_3 (%)	1.49	7.80	4.01
Cl^- (%)	0.03	0.04	0.02
CaO_{free} (%)	-	9-11	2.58-6.0
App. specific gravity (kg/m^3)	3.14	2.42	2.44
Fineness R_{45} (%)	1.50	19-25	20-35

Table 2. Composition and strength results of the concrete series tested with total cementitious content 300 kg/m³

Mixture No	CEM I42.5N/Fly ash F1,F2	w/cementitious	28-d compressive strength* (MPa)	
			Fly ash F1	Fly ash F2
1	180/120	0.48	46.0	44.0
2	180/120	0.50	45.0	43.0
3	180/120	0.54	42.0	39.0
4	180/120	0.60	31.0	28.0

*mean value of six cubes 15x15x15 cm

Table 3. Calculated k-values for concrete with 30% and 40% fly ash type F1

Cementitious content (kg/m^3)	Fly ash F1 30%				Fly ash F1 40%			
	0.4	0.5	0.6	0.7	0.4	0.5	0.6	0.7
280	-	-	0.84	1.00	-	-	0.84	1.00
300	1.36	1.13	0.98	0.81	1.27	1.10	0.99	0.91
350	1.17	1.06	0.98	0.91	1.17	1.06	0.99	0.93
370	1.43	1.26	1.14	1.06	1.33	1.20	1.11	1.05

Table 4. Calculated k-values for concrete with 30% and 40% fly ash type F2

Cementitious content (kg/m^3)	Fly ash F2 30%				Fly ash F2 40%			
	0.4	0.5	0.6	0.7	0.4	0.5	0.6	0.7
280	-	-	-	0.82	-	-	0.70	0.86
300	1.22	1.01	0.88	0.78	1.16	1.01	0.91	0.84
350	0.96	0.85	0.78	0.73	0.97	0.89	0.84	0.80
370	0.88	0.87	0.86	0.85	0.91	0.90	0.89	0.89

Fig. 1 Granulometry of limestone aggregates used for all tested concrete mixtures

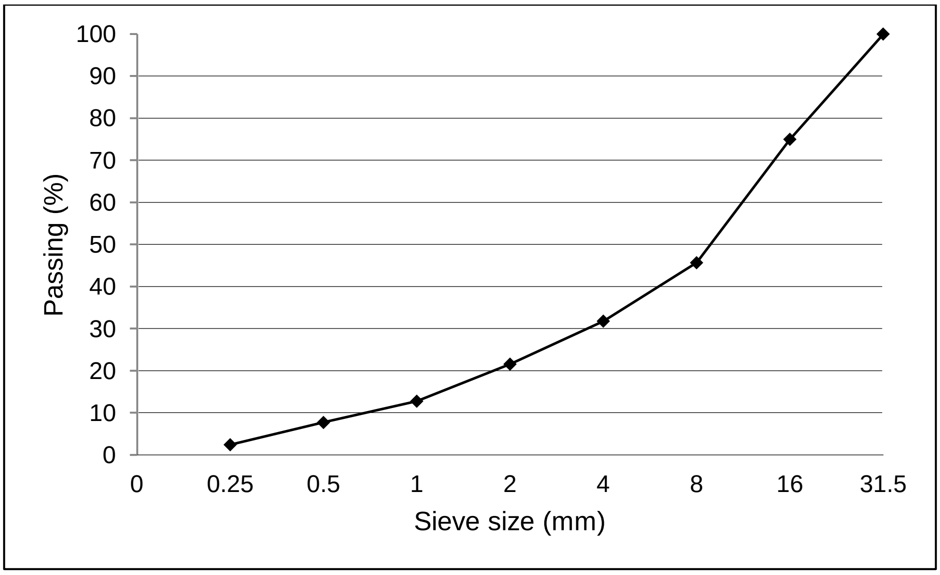

Fig.2-5 Compressive strength versus water/cementitious relationships after regression for control and with 40% cement replacement by fly ashes F1, F2

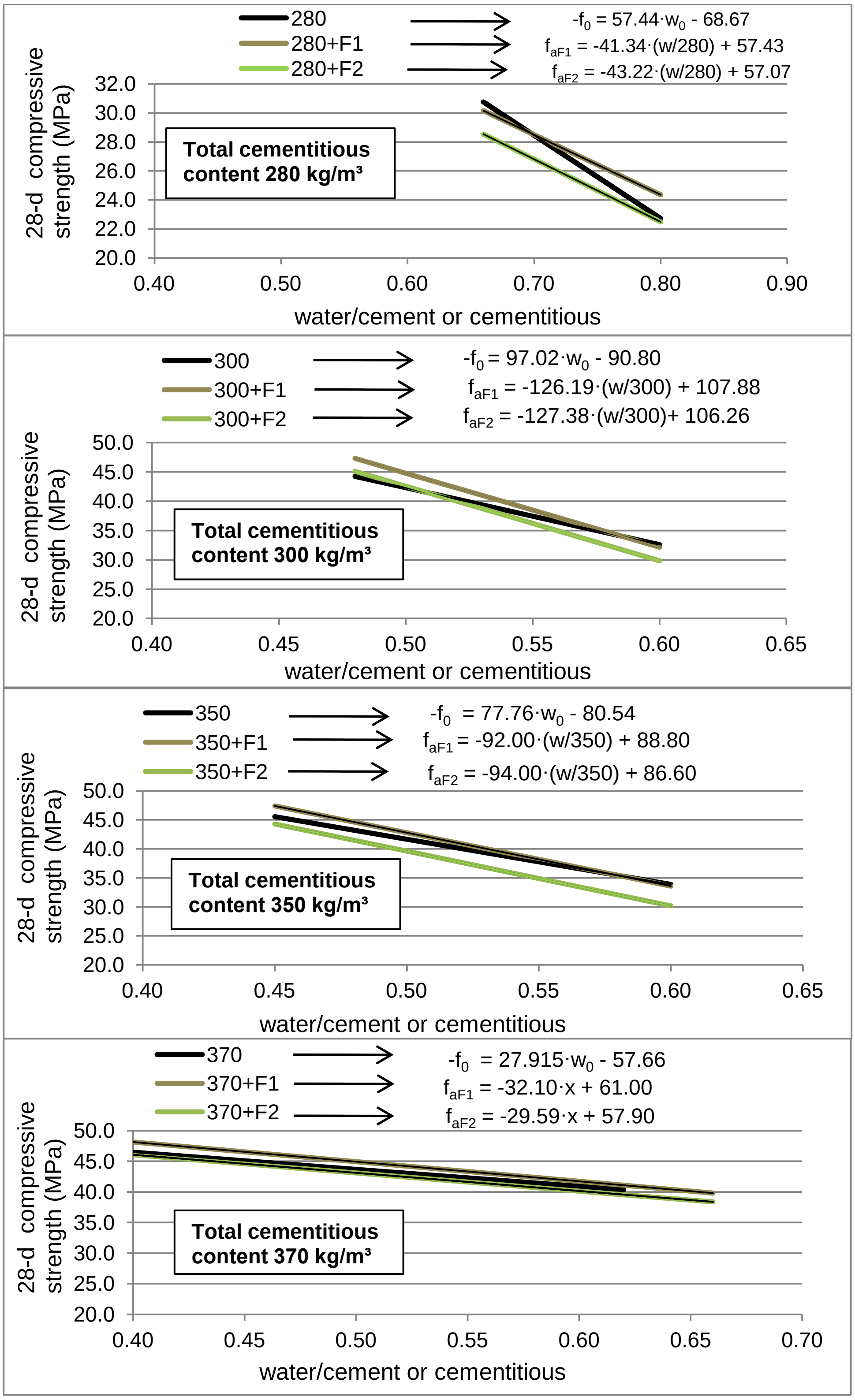

Fig.6-9 Influence of fly ash addition to 28-d strength development