

FLY ASH AS BINDER IN CONCRETE

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ABSTRACT

Research efforts over the past years towards an effective utilisation of fly ash in concrete have lead to a quantitative understanding of the efficiency factor (k-value) of fly ash. For that KEMA developed a uniform determination method, based on starting points from previous research work. Measurements of the k-value of Dutch fly ashes during the last 7 years show that the mean k-value increased from 0.42 up to 0.75 with a decreasing mean standard deviation from 0.20 to 0.11. This is the result of quality control, blending of coal mixtures and better firing techniques.

1 INTRODUCTION

The use of fly ash in concrete is becoming more and more important, because of economical and technical reasons. Cement (the expensive part of concrete) can partly be replaced by fly ash. The quality of fly ash used in this market segment must be guarded very strictly. In the Netherlands several standards are used for the quality control of fly ash concrete with fly ash as admixture and cement. These standards are:

- NEN 5950 for concrete
- NEN 3550 for cement
- CUR 26 and NEN EN 450 for fly ash

For an effective utilisation of fly ash in concrete a quantitative understanding of the efficiency of fly ash is essential. A lot of research has been performed over the last decades. This has lead to an efficiency factor (k-value) in the Dutch standards of 0.2 for fly ash in combination with CEM I cement. KEMA has performed k-value measurements of Dutch fly ash over the last eight years. Review of research work from other laboratories showed that it is necessary to develop a uniform determination method for measuring the k-value.

In this present paper an evaluation of k-value measurements and method is presented.

2 FLY ASH IN CONCRETE

In the Netherlands it is nowadays common to use fly ash as mineral admixture in concrete. Therefore the properties of fly ash must satisfy the requirements in EN 450. Concrete must meet the requirements in accordance with NEN 5950. To fly ash in combination with CEM I cement (in all environmental classes) and CEM III (in environmental class 1) an efficiency factor (k-value) of 0.2 may be adjudged in spite of the minimal cement content.

The total binder content (cement plus fly ash) is determined with the formula $(c+k.f)$ where c =cement content, k =k-value, f =fly ash content.

Evaluation of research work of investigators in other countries showed that in some cases higher k-values are adopted. In the German standards k-values up to 0.7 are allowed. A very important aspect in the evaluated research work showed to be the determination method of the k-value. There is no uniform determination method. Because of the influence of many parameters like water to cement ratio and concrete age, it is necessary to develop a uniform method.

3 PRINCIPLE OF THE K-VALUE

The cementing efficiency (k-value) of fly ash is defined as that portion of fly ash that can be used as cement without effecting the properties of the concrete in relation to concrete that does not contain fly ash. In common the compressive strength is used as a criterion for the determination of the k-value. However, also the durability properties like carbonation or permeability can be used as criterion.

In figure 1 the principle of the k-value calculation is given. The k-value is calculated as follows:

$$\omega_{\phi} = \omega / (1 + k \cdot \phi) \quad k = (\omega / \omega_{\phi} - 1) \cdot 1 / \phi$$

where:

ω = water/cement ratio fly ash concrete

ω_{ϕ} = water/cement ratio of concrete without fly ash

ϕ = ratio fly ash/cement

The relation between water/cement to ratio and compressive strength of concrete has been described many times in the literature. Abrams, Ferret, Walz, Weber and Wesche have established an empirical relation between compressive strength, cement standard strength, concrete age, water to cement ratio and fly ash to cement ratio. The calculation method for determining the k-value, based on the empirical relationship, is very complicated because of seven parameters in the equation. KEMA developed a simplified calculation method with two parameters based on the linear relationship between the compressive strength and reciprocal water/cement ratio dependent on the cement type, water/cement ratio, concrete age and binder content (figure 3).

The formula for this relationship is for reference concrete without fly ash:

$$f_c = A + B/\omega_r$$

where

f_c = the compressive strength and ω_r is the water/cement of ratio of the reference.

and for fly ash concrete:

$$f_c = P + Q/\omega$$

where

f_c = is the compressive strength and ω is the water/cement of ratio fly ash concrete.

A, B, P and Q are parameters which can be calculated from data of reference and fly ash concrete mixtures.

4 FACTORS INFLUENCING THE K-VALUE

The efficiency factor (k-value) of fly ash is influenced by numerous variables in terms of the characteristics of fly ash and cement as well as the parameters influencing the concrete mix design itself. The influence on the cementing efficiency of fly ash depends on the following characteristics:

For fly ash:

- physical properties like particle shape, size and distribution
- chemical properties like composition, glass content and pozzolanicity.

For cement:

- physical properties like particle size and distribution
- chemical properties like composition, slag content and alkali content

For concrete mix:

- total binder content
- fly ash content
- curing method and time
- temperature
- water to cement ratio.

Because of the influence of the fly ash type as well as the cement type it is not possible to define an efficiency factor (k-value) for only one fly ash type. The k-value of a certain fly ash type should be determined in combination with a cement type.

Binder content

Minor compressive strength variations have much influence on the k-value. The compressive strength decreases when the cement content increases, because cement stone has a lower elasticity modulus than aggregate. Therefore, it is important to define the total content (c+f). In figure 2 the compressive strength versus the total binder content (c+f) for a constant water to cement ratio is given for fly ash concrete and concrete without fly ash (reference). The difference between the compressive strength of fly ash concrete (260 kg/m³ - point A) and the reference concrete (360 kg/m³ - point D) is smaller than between point B (fly ash concrete 360 kg/m³) and point C (reference 260 kg/m³). Therefore it is very important to select a reference and fly ash concrete mixture with constant total binder content.

Curing method and age

The consequence of use of fly-ash in concrete could be an increase in sensibility for curing, because of the delayed pozzolanic activity of fly ash. Research showed that only at the first three days, wet curing was necessary. The influence of the pozzolanic activity of fly ash in combination with CEM I cement is evident. In combination with CEM III cement this pozzolanic activity is less. The conclusions that the k-value increases with increasing age of the concrete.

Temperature

The influence of a lower temperature (10 °C) on the k-value is negligible.

Fly ash content

A fly ash content in the range $f/c = 0.18$ until 0.33 has a negligible influence on the k-value for CEM I and CEM III cements.

Water to cement ratio

The k-value is highly dependent on the water/cement ratio of the fly ash concrete. If the water/cement ratio increases, the k-value decreases. This is caused by the delayed pozzolanic activity of the fly ash. In table 1 and 2 and figure 3 the linear relationship between water/cement ratio and compressive strength are given for a reference and fly ash concrete. According to the standards a maximum water/cement ratio of 0.65 is allowed. This agrees with a water/cement ratio for fly ash concrete of 0.72 and a water/cement + fly ash ratio of 0.58. The difference in regression coefficients between reference and fly ash concrete causes the dependence of the k-value on the water/cement ratio. If the starting point for a k-value determination is a "worst case" approach, then k-values should be determined at water/cement ratios 0.72 (water/binder ratio 0.58) for the fly ash concrete.

5 DEFINITION OF STARTING POINTS OF THE K-VALUE DETERMINATION

The performed research on the influence factors of the k-value has lead to formulating starting points for a uniform determination method. This method has to be performed for each fly ash/cement combination. K-values should always be determined at prescribed water/cement ratios. With a general k-value of a fly ash type in combination with a given cement type is meant a k-value which has been determined according to the following rules:

- water/cement + fly ash ratios for fly ash from 0,60 until 0,45
- constant cement + fly ash content of reference and fly ash concrete
- a curing time of 28 days; humidity > 95%.

Because of the effect of sensitivity of the k-value for slight differences in compressive strength, it is important to determine every measuring point accurately (three times).

6 K-VALUES OF DUTCH FLY ASHES

KEMA performs the quality control of Dutch fly ashes by order of the Dutch Fly ash Corporation since 1988. Since 1989 also measurements of the k-value of fly ashes in combination with CEM I 32.5R are carried out at water/cement + fly ash ratio 0.60. In figure 4, k-values of Dutch fly ashes from several power plants after 28 days curing are given. As can be seen in figure 4 the efficiency factor k of Dutch fly ashes has increased since 1995 with about 35% to a value of 0.75. Also the standard deviation decreased from 0.20 to 0.11. This is the result of quality control of the Dutch fly ashes, the use of coal mixtures (blends) and better firing techniques.

7 CONCLUSIONS

The k-value of Dutch fly ashes, measured in combination with CEM I cement, has increased over the years. At this moment the k-value has a mean value of 0.75 with a standard deviation of 0.11 at a water/cement + fly ash ratio of 0.60. This is the result of quality control, the use of blend coal mixtures and better firing techniques.

A review of research work performed by German and Dutch researchers showed that a uniform determination is needed. KEMA developed a determination method based on previous research being:

- the k-value applies to a given fly ash type in combination with a given cement type
- the k-value is dependent on the water/cement ratio
- the k-value should be measured at a constant binder content for fly ash and reference concrete
- the k-value should be measured at a curing time of 28 days and a humidity of > 95%.

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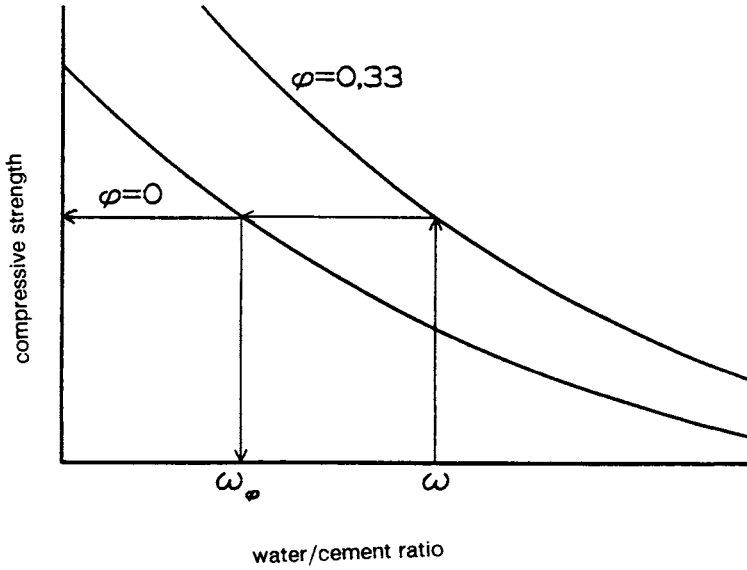


Figure 1 Principle of the k-value

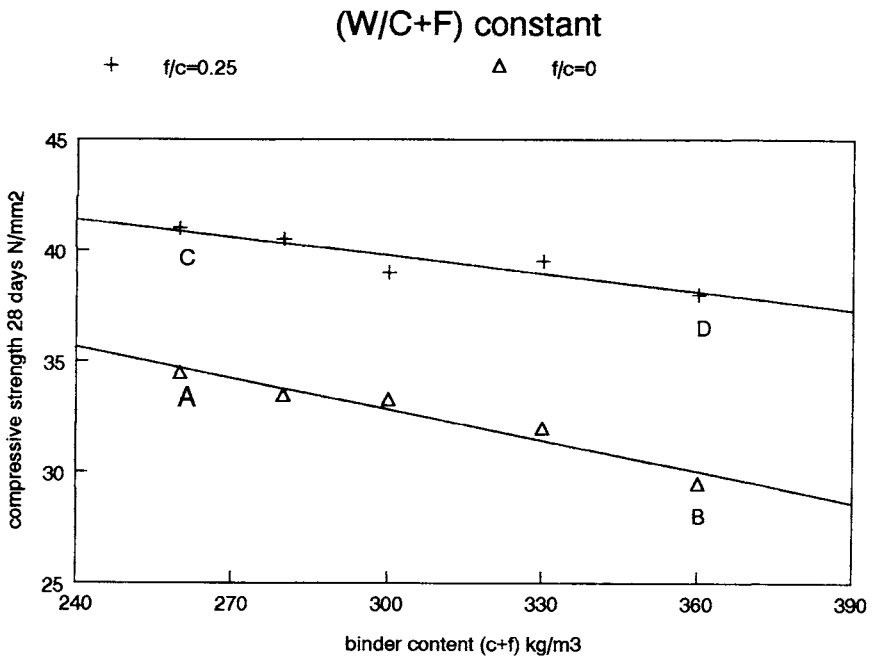


Figure 2 Influence binder content concrete

K-VALUE DETERMINATION

Table 1 Compressive strength reference at different water/binder ratios

water/binder ratios	compressive strength N/mm ²
WBF 0.40	59.8 - 59.7 - 61.2
WBF 0.50	46.1 - 43.8 - 45.6
WBF 0.55	37.2 - 36.3
WBF 0.60	32.9 - 31.7 - 32.4

Table 2 Compressive strength fly ash concrete at different water/binder ratios

fly ash sample	WBR 0.45	WBR 0.48 - 0.49	WBR 0.65
va-1	45.1	40.4	21.7
va-2	44.1	41.4	18.8
va-3	44.7	40.1	19.3
va-4	44.2	41.3	18.7

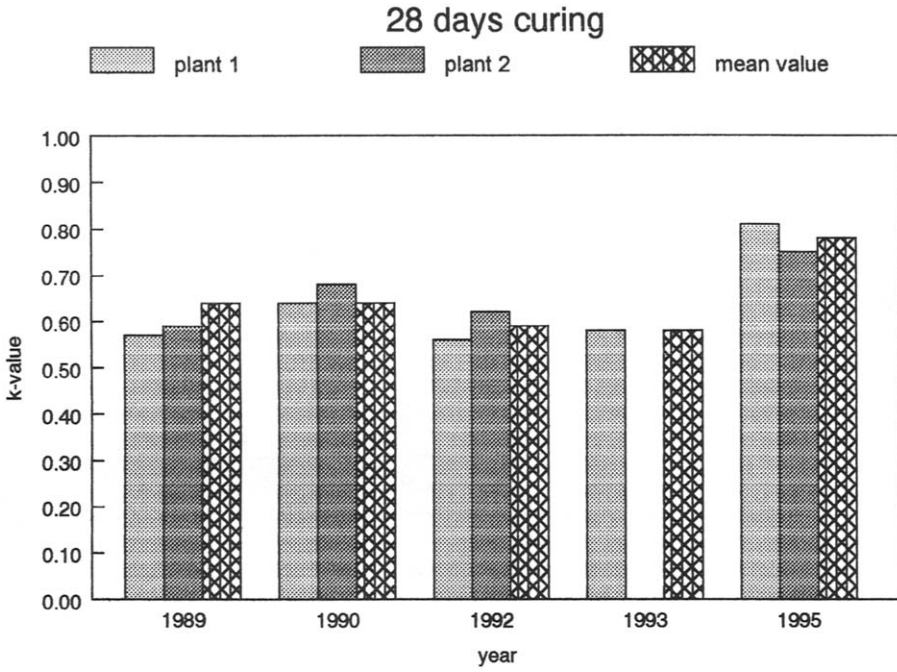


Figure 4 K-values Dutch fly ashes

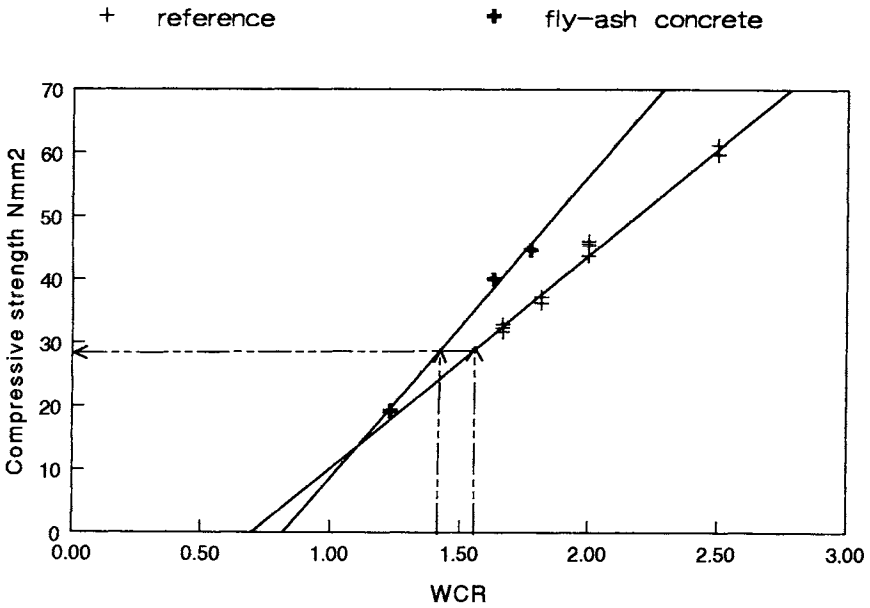


Figure 3 K-value of fly ash 28 days curing