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EFFICIENCY OF FLY ASH IN CONCRETE WITH AGE

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ABSTRACT

Research efforts over the past many decades towards an effective utilisation of fly ash in concrete do not seem to have led to a quantitative understanding of the efficiency of fly ash as a mineral admixture, particularly because of the vast variation in the grades of concrete and the different levels of replacements adopted. This paper is an effort directed towards a specific understanding of the efficiency of fly ash in concrete, considering the strength to water cement ratio relations, age and percentage of replacement. The "overall cementing efficiency" (k) of fly ash was established through a "general efficiency factor" (k_e), dependent on the age and a "percentage efficiency factor" (k_p), dependent on the replacement percentage. This information will allow designers to evaluate the strength of well designed fly ash concretes at any age and at the different percentages of replacement.

Introduction

A quantitative understanding of the efficiency of fly ash as a mineral admixture in concrete is essential for its effective utilisation. Research efforts in the past have not been successful in quantifying this efficiency because of the numerous variables involved, both in terms of the characteristics of fly ash and cement as well as the parameters influencing the concrete mix design it self. Initially, the use of fly ash started as direct replacement of cement in concrete, which is still advocated by a few [1]. Later efforts towards an effective utilization led to rational methods of incorporating fly ash in concrete, considering the fact that the two concretes (with or without fly ash) can be made to reach the same strength at a given age by adjusting their water cementitious materials ratios [2]. This was done either by adjusting the quantity of fly ash introduced for replacing the cement or through the "cementing efficiency factor" of fly ash.

In general, it was observed that fly ash exhibits very little cementing efficiency at the early ages and acts rather like fine aggregate (filler), but at later ages the pozzolanic property becomes effective leading to a considerable strength improvement. This obviously means that the cementing efficiency of fly ash improves with age due to the pozzolanic reaction. It is also observed that this cementing efficiency of fly ash depends on many of its characteristics -

physical properties like particle shape, size and distribution, chemical properties like composition, glass content etc. Other parameters related to cement and the ones effecting mix proportioning can also influence the resulting concrete behaviour significantly. Several investigators reported the effect of fly ash in concrete through a comparison of the compressive strength of fly ash concretes with the normal concretes. The variation of strength with age was also discussed by a few [3-6]. In spite of all these investigations, it is felt that there is a lack of quantitative understanding of the behaviour of fly ash in concrete [7]. The present paper deals with the efficiency of fly ash in concrete, through the strength to water cement ratio relations of these concretes at different ages and at the varying percentages of replacement.

Efficiency of Fly Ash

The simple and modified replacement techniques of yester years appears to have limited the replacement levels to a maximum of about 25 - 35%, as suggested by the latest ACI committee recommendations [1]. A rational method of proportioning fly ash concrete was first proposed by Smith [2], in which the "fly ash cementing efficiency factor" (k) was defined in such a way that the strength to water cement ratio relation for normal concretes is also valid for fly ash concretes considering the "effective water cement ratio", as given by $[w/(c + kf)]$. Based on the results of an experimental investigation he suggested a value of 0.25 for this cementing efficiency "k" of fly ash for replacements up to 25%. Later, the German standards adopted a value of 0.3 for replacements of 10 - 25%. The British code recommended a value of 0.3 for replacement percentages up to 50%. The most recent CEB-FIP model code proposes an efficiency value of 0.4 for replacements between 15 - 40%. It was reported [8] that the Danish standards stipulate an efficiency value of 0.5, and can allow even higher efficiency factors if proven through an appropriate study. Schiessl [9] reported that for the concretes with different types of cements and fly ashes (up to 28% replacement and w/c ratio between 0.5 and 0.65) a value of 0.5 is more appropriate for the efficiency factor.

All the above information clearly shows that a single efficiency value is recommended presently, limiting the replacement level to a specified maximum. However, it was also suggested by Schiessl [9] that the cementing efficiency of fly ash is dependant not only on the water cementitious materials ratio but will also depend up on the level of replacement. Recent research efforts have also shown ways of incorporating high volumes of fly ash in concrete, with percentage replacement levels up to 75% [10]. Considering the above facts, the present investigation is an effort to understand the cementing efficiency of fly ash in concrete at the different ages of 7,28 and 90 days and at percentage replacement levels ranging from 15 - 75% by re-evaluating the results of earlier investigators [11-22].

Evaluation of Efficiency

The cementing efficiency of a pozzolan is defined as the number of parts of cement that could be replaced by one part of pozzolan without changing the property being studied. In the present paper the efficiency of fly ash was estimated by trying to bring together the water cementitious material ratio to strength relations for both normal and fly ash concrete. In principle this was done by using the " w" concept, which attempts to bring the water cementitious materials ratio $[w/(c + f)]$ nearer to the water cement ratio of the control concrete (w/c_o) by applying the cementitious efficiency of fly ash "k" at any particular strength. However,the first trial to bring the water cementitious materials ratios to strength relations through a single value (general efficiency factor, k_e), did not lead to a good correlation at all the percentages of replacement. At this stage, the remaining differences were corrected through the "percentage efficiency factor" (k_p). The "overall cementing efficiency" (k) of fly ash is thus the sum total of "k_e" and "k_p". A detailed presentation of this method for evaluation of the efficiency of fly ash in concrete was discussed in detail earlier [23-25]. Thus the water cement ratio (w/c_o) to strength relation of normal concretes will be the same for fly ash concretes, by considering the "water to effective cementitious materials ratio" $[w/(c + kf) = w/(c + k_ef + k_pf)]$.

It is also a fact that the quality of cement improved significantly over the past couple of decades [26]. The quality of fly ash also improved due to the use of pulverized fuels and high efficiency collection systems. In view of the above only the results of about twelve major investigations during the past ten years were chosen for an evaluation [11-22], from over a hundred reported. It was made sure that these will form a fairly representative group governing all the major parameters that influence the behaviour of fly ash in concrete and present the complete information required for such an evaluation. In all about 100 concretes from the above investigations were evaluated. During evaluation some of the concretes were deleted from the data due to larger size aggregates (above 20 mm), high superplasticizers content (over 2%), different curing conditions (higher temperatures), etc. Finally about 70 concretes made with ordinary Portland cement and cured under normal conditions were evaluated. All the fly ashes used confirm to the minimum characteristics specified by ASTM C 618 for use as mineral admixture in concrete. Also, different researchers used specimens of different sizes and shapes and all these have been converted to their equivalents for a cube of 15 cm size through accepted guide lines [27]. Table. 1 presents the general details of the concretes evaluated in this study.

The water cementitious materials ratio $[w/(c + f)]$ to compressive strength relations at the different percentages of replacement were plotted for all the concretes at 7, 28 and 90 days. Typical relationships for the 90 days strength of these concretes were presented in Fig. 1. Similar figures for the 7 and 28 days were already reported earlier [23, 25]. It can be seen from Fig. 1 that at 90 days the compressive strength of concretes containing fly ash up to 20% replacement were all slightly above that of normal concrete and at all other percentages the relationships were below that of normal concrete.

In order to bring the strength values at all replacements levels nearer to that of normal concrete the water cementitious materials ratios were modified through a single factor, termed as "general efficiency factor" (k_e), replacing the $[w/(c + f)]$ by $[w/(c + k_ef)]$. After several trails with "k_e" values varying from 0.1 to 0.8, the appropriate "k_e" values were found to be 0.3, 0.5 and 0.6 for the 7, 28 and 90 day strengths of these concretes. It can be seen that the k_e values were increasing with the age but rate of increase was lower at higher ages [Fig. 2]. As already reported earlier [23-25], it was observed that this general efficiency factor "k_e" could not bring the $[w/(c + k_ef)]$ to strength relations very close to the water cement ratio of normal concrete $[w/c_o]$ at all percentages.

At this juncture, the effect of percentage replacement on efficiency, which can bring the fly ash concrete strength values closer to that of normal concrete were found by evaluating the remaining difference through a "percentage efficiency factor" (k_p). The typical variation of strengths with $w/(c + k_ef + k_pf)$ at 90 days were presented in Fig. 3. This shows that by adopting the two efficiency factors "k_e" and "k_p" the strengths of fly ash concretes at different ages and at different percentages could be brought close to that of normal concrete. Fig. 4 presents a comparison of the overall predictions at 7, 28 and 90 days after modifying with "k_e" and "k_p". Also, the regression coefficients for the prediction of fly ash concretes were found to be

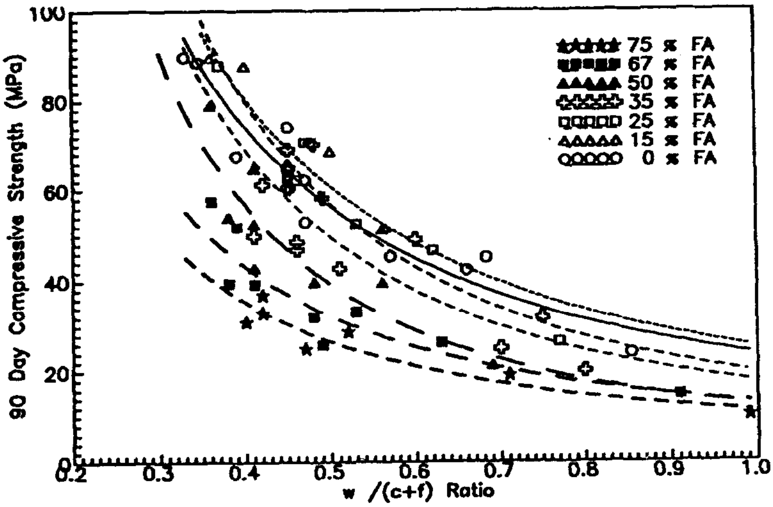

FIG. 1.
Variation of Strength with w/(c + f).

0.93, 0.95, and 0.94 for 7, 28 and 90 days respectively, while the same for the normal concretes was about 0.95 at all the ages.

The variation of the "percentage efficiency factor" (k_p) with the fly ash replacement percentage at the different ages of 7, 28 and 90 days was presented in Fig. 5. This shows that

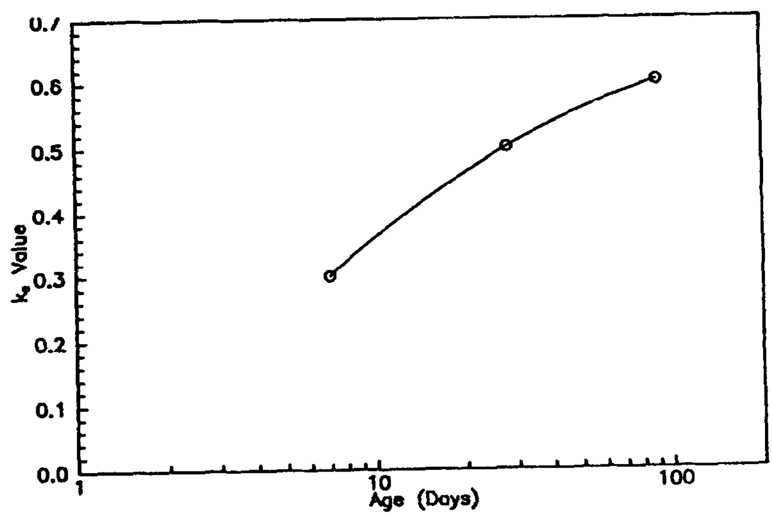

FIG. 2.
Variation of General Efficiency Factor (k_e) with Age.

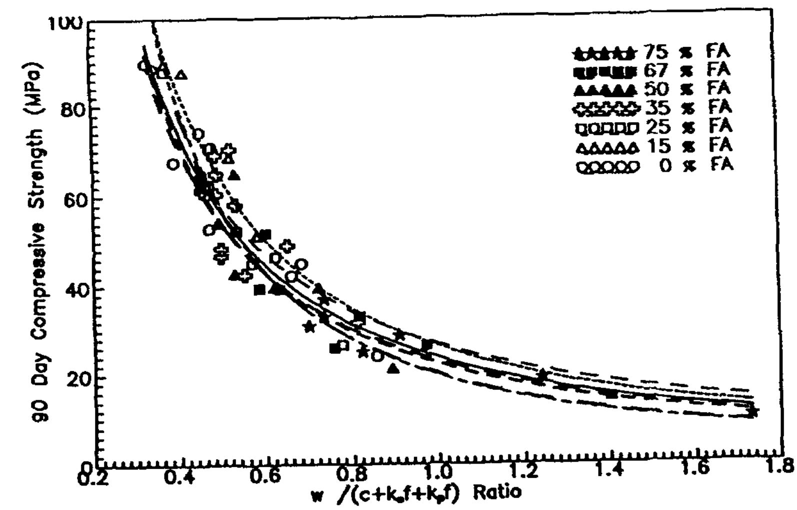

FIG. 3.
Variation of Strength after Correcting for k_e and k_p.

the value of "k_p" was almost the same at all the ages studied. Also, the percentage efficiency factor was decreasing with increasing the replacement level and at about 45% replacement the value of k_p was almost zero. The variation of "k_p" with the percentage replacement [as a ratio, $p = f/(c + f)$ varying between 15 - 75%] was found to be

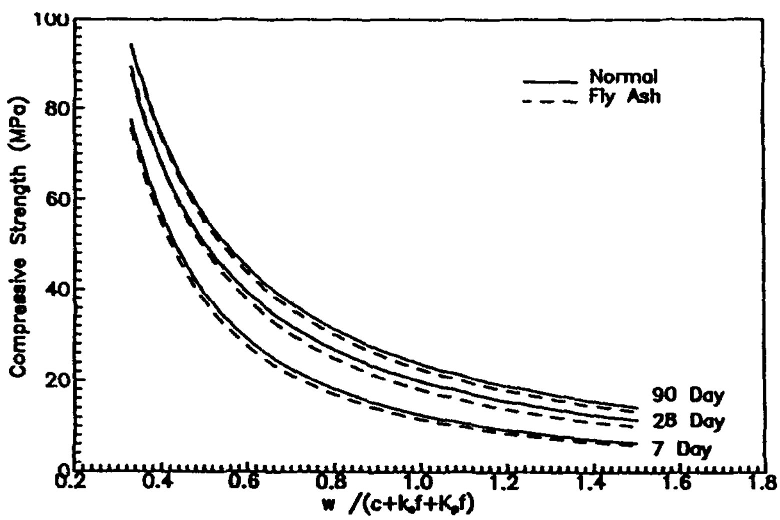

FIG. 4.
Variation of Strength with w/(c + kef + kpf) at Diofferent Ages.

$$k_p = 2.54\,p^2 - 3.62\,p + 1.13 \quad (1)$$

The "overall cementing efficiencies" ($k = k_e + k_p$) at the different ages studied were also presented in Fig. 5. The corresponding relationships for the overall cementing efficiencies (k_7, k_{28} and k_{90}) at 7, 28 and 90 days for replacement levels varying from 15 -75% were found to be

$$k_7 = 2.67\,p^2 - 3.75\,p + 1.45 \quad (2)$$

$$k_{28} = 2.78\,p^2 - 3.80\,p + 1.64 \quad (3)$$

$$k_{90} = 2.50\,p^2 - 3.59\,p + 1.73 \quad (4)$$

The above investigations show that the efficiency of fly ash is dependent on both age [k_e] and the percentage replacement [k_p], unlike the single value for "k" proposed hitherto [2,9]. Furthermore, the value of "k" even at 75% replacement was about 0.33 at 28 days, which was higher than the value of 0.25 reported by Smith [2]. It was observed that the overall cementing efficiencies of fly ash varied from a value of about 0.95 - 0.13, 1.15 - 0.33, and 1.25 - 0.43 for replacement percentages ranging from 15 - 75%, at the 7, 28 and 90 days studied. The study also revealed that the efficiency values vary slightly with the type of cement, type of aggregates, cement content, curing conditions etc. These efficiency values "k_e", "k_p" and "k" were only the average values at the different percentages of replacement for ordinary Portland cement, normal type of aggregates and normal curing conditions. Table 1. also proposes the permissible values which could be useful in formulating codal provisions. These were defined considering the fact that it is best to limit the percentage replacement to a maximum of 50% and even so the proposed values were only 80% of the average values obtained in the present evaluation.

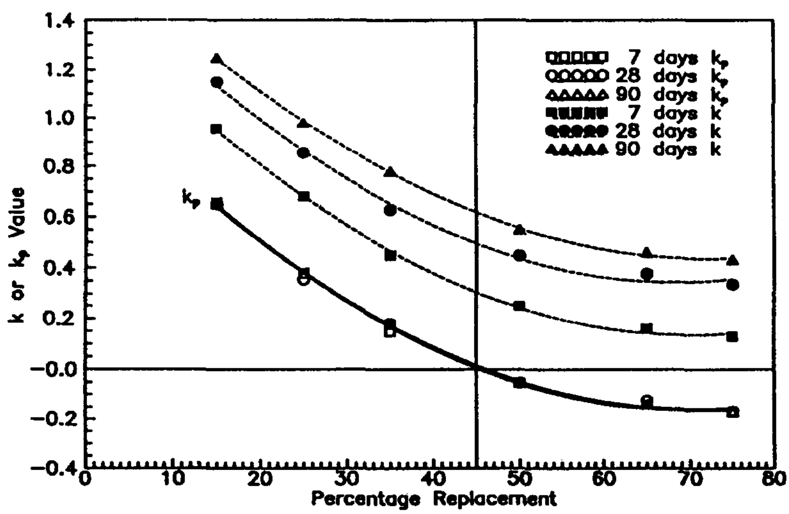

FIG. 5.
Variation of Efficiency Factors k_p and k.

TABLE 1

Details of Concretes Evaluated and the Efficiences

S. no.	% Rep.	Type	w/(c = f) Range	Slump Range (mm)	Comp. Strength (Mpa)			Average & Recommended* Efficiences			Reference Numbers
					7 Day	28 Day	90 Day	7 Day	28 Day	90 Day	
1	0	—	0.33–0.85	20–120	15–69	22–80	24–90	—	—	—	12, 14, 16–21
2	15	F	0.36–0.50	05–80	30–56	43–75	51–90	0.95 (0.75)	1.15 (0.09)	1.40 (1.10)	12, 15, 21
3	25	F C	0.37–0.77 0.40–0.62	10–130 90–110	17–57 24–36	22–71 38–55	27–88 47–62	0.69 0.69 (0.55)	0.86 0.98 (0.65)	1.07 1.01 (0.75)	12, 16, 19 19, 20
4	35	F C	0.42–0.75 0.41–0.60	05–100 90–110	15–38 24–33	22–55 41–52	32–69 48–65	0.43 0.44 (0.35)	0.62 0.64 (0.50)	0.81 0.81 (0.60)	11, 12, 18 15, 20
5	50	F C	0.36–0.56 0.36–0.90	10–35 00–40	15–40 06–28	27–54 09–44	40–79 18–54	0.25 0.23 (0.20)	0.44 0.45 (0.35)	0.55 0.55 (0.45)	12, 21 13, 14, 17, 22
6	65	C	0.38–0.91	00–100	04–12	09–42	15–61	0.16	0.38	0.46	13, 14, 20
7	75	C	0.30–0.99	00–50	02–12	08–40	10–37	0.13	0.33	0.41	13, 14, 22

*Recommended efficiency values are given in brackets

Factors Influencing the Efficiency of Fly Ash

In an earlier review it was reported that the cementing efficiency of fly ash will vary depending up on the type of cement, fly ash, age etc [28]. A later investigation showed that the efficiency of fly ash is dependent not only on the physical and chemical characteristics of fly ash, but will also be influenced by mix design parameters, strength range, addition level and age [29]. In contrast, a recent study [8] reports that effect of water cement ratio on efficiency was minor even for different types of cement. It was also stated by them that while the type of fly ash has no significant influence on the efficiency factors, the type of cement had some effect. Also, the "k" value increased with age for ordinary Portland cement and the curing period and temperature were found to have some effect on the efficiency.

It was felt that the different conclusions drawn by the above investigators and even by many others earlier were all based on limited experimental investigations. It was thus decided to re-evaluate the data chosen earlier to study the effect of fly ash type presently, to assess the effect over a wide range of water cementitious materials ratios, percentage replacement and strength at different ages. Fig. 6. shows the results of the above evaluation. It is clear from this that the efficiency did not depend upon the type of fly ash (class C or F, both confirming to the ASTM specifications). However, it is to be recognised that if the concretes are significantly modified through the use of superplasticizers and other chemical admixtures or even high temperature, the efficiencies evaluated could be very much different.

Conclusions

This study was primarily concerned with the re-evaluation of the efficiency of fly ash in concretes containing ordinary Portland cement (ASTM type II) from the investigations reported

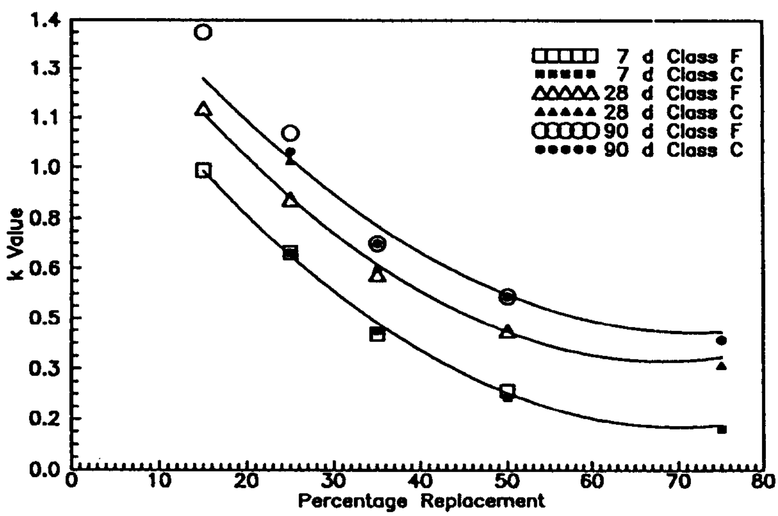

FIG. 6.
Efficiency Factors with Fly Ash Class

in recent years. The replacement levels in the concretes studied varied from 15 - 75% and the strength efficiencies at the 7, 28 and 90 days were calculated for concretes cured at laboratory temperatures. However, concretes containing larger size aggregates (above 20mm), higher dosages of superplasticizers (over 2%) or cured at higher temperatures were not included.

The "overall cementing efficiencies" (k) were assessed as a combination of the two different efficiencies, the "general efficiency factor" (k_e) and the "percentage efficiency factor" (k_p). The evaluations led to the following basic conclusions.

1. The "general efficiency factors" (k_e) evaluated at 7, 28 and 90 days were found to be 0.3, 0.5 and 0.6 respectively.
2. The "percentage efficiency factors" (k_p) evaluated after correcting for the above "k_e" showed that it did not depend on the age of concrete.
3. Combining the above two efficiency factors the "overall cementing efficiency" (k) of fly ash at replacement levels varying between 15 - 75% showed that they vary from 0.95 - 0.13, 1.15 - 0.33 and 1.25 - 0.43 at the different ages of 7, 28 and 90 days respectively. This shows clearly that the "overall cementing efficiency" (k) of fly ash cannot be adequately represented by a single value as reported by many todate. For ease in adopting this information in codal provisions, safe values of "k" were also proposed.
4. It was also observed that the overall cementing efficiencies were nearly the same for both "F and C type" fly ashes.
5. Lastly, the efficiencies reported could be helpful in the design of fly ash concretes of any specific strength and at any age with greater confidence.

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