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An experimental study on strength development of concrete containing fly ash and optimum usage of fly ash in concrete

A. Oner[a,*], S. Akyuz[b], R. Yildiz[a]

[a]Department of Civil Engineering, Faculty of Engineering, Kocaeli University, Kocaeli 41010, Turkey

[b]Department of Civil Engineering, Faculty of Civil Engineering, Istanbul Technical University, Maslak, Istanbul 80626, Turkey

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Abstract

This paper presents a laboratory study on the strength development of concrete containing fly ash and optimum use of fly ash in concrete. Fly ash was added according to the partial replacement method in mixtures. A total of 28 mixtures with different mix designs were prepared. 4 of them were prepared as control mixtures with 250, 300, 350, and 400 kg/m^3 cement content in order to calculate the Bolomey and Feret coefficients (K_B, K_F). Four groups of mixtures were prepared, each group containing six mix designs and using the cement content of one of the control mixture as the base for the mix design. In each group 20% of the cement content of the control mixture was removed, resulting in starting mixtures with 200, 240, 280, and 320 kg/m^3 cement content. Fly ash in the amount of approximately 15%, 25%, 33%, 42%, 50%, and 58% of the rest of the cement content was added as partial cement replacement. All specimens were moist cured for 28 and 180 days before compressive strength testing. The efficiency and the maximum content of fly ash that gives the maximum compressive strength were obtained by using Bolomey and Feret strength equations. Hence, the maximum amount of usable fly ash amount with the optimum efficiency was determined.

This study showed that strength increases with increasing amount of fly ash up to an optimum value, beyond which strength starts to decrease with further addition of fly ash. The optimum value of fly ash for the four test groups is about 40% of cement. Fly ash/cement ratio is an important factor determining the efficiency of fly ash.

Keywords: Calcium–silicate–hydrate (C–S–H); Compressive strength; Fly ash; Optimum usage

1. Introduction

Mineral admixtures such as silica fume, fly ash, and ground granulated blast-furnace slag improve the engineering properties and performance of concrete when they are used as mineral additives or as partial cement replacements [1,2]. Economic (lower cement requirement) and environmental considerations have also played a great role in the rapid increase in usage of mineral admixtures. Compared with Portland cement, cement with pozzolan helps to have concrete with less permeability and a denser calcium silicate hydrate (C–S–H) is obtained. Ground granulated blast-furnace slag, silica fume, metakaolin, and rice-husk ash can be used in concrete as supplementary cementing materials (SCM) in addition to fly ash. Compared to fly ash, the availability of these materials is rather limited. One of the major institutional barriers against the use of fly ash and other supplementary cementing materials is the prescriptive type of specifications and standards [3–5].

Fly ash is a by-product of the coal power generation and consists mainly of SiO_2, Al_2O_3, Fe_2O_3, and CaO and some impurities. According to ASTM C618 [6], fly ash belongs to Class F if (SiO_2+Al_2O_3+Fe_2O_3)>70%, and belongs to Class C if 70%>(SiO_2+Al_2O_3+Fe_2O_3)>50%. Usually, Class F fly ashes have a low content of CaO and exhibit pozzolanic properties, but Class C fly ashes contain up to 20% CaO and exhibit cementitious properties.

* Corresponding author. Tel.: +90 262 335 1148 2222; fax: +90 262 335 2812.

E-mail addresses: adnan@kou.edu.tr, adnanoner2001@yahoo.com (A. Oner).

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Low-calcium fly ash (FL) is produced by burning anthracite or bituminous coal, and high-calcium fly ash (FH) is produced by burning lignite or sub-bituminous coal. FL is categorized as a normal pozzolan, a material consisting of silicate glass, modified with aluminum and iron [7,8]. The mechanism is that when pozzolanic materials are added, calcium hydroxide $Ca(OH)_2$ is transformed into secondary calcium silicate hydrate (C–S–H) gel, causing the transformation of larger pores into finer pores as a result of pozzolanic reaction of the mineral admixtures. Hydrated cement paste contains approximately 70% C–S–H, 20% $Ca(OH)_2$, 7% sulpho-aluminate, and 3% of secondary phases. The $Ca(OH)_2$, which appears as the result of the hydration, affects the quality of the concrete negatively by forming cavities because of its solubility in water and its low strength. The use of mineral admixtures has a positive effect on the quality of the concrete by binding the $Ca(OH)_2$ [9–11]:

$$\text{Cement hydration: Cement}(C_3S, C_2S) + H_2O \rightarrow CSH - \text{gel} + Ca(OH)_2$$

$$\text{Pozzolanic reaction: } Ca(OH)_2 + SiO_2 \rightarrow CSH - \text{gel}$$

The fly ash concrete mix techniques can generally be divided into three main categories. Simple replacement method involves direct weight replacement of a part of Portland cement with fly ash, with a subsequent adjustment of concrete for yield. Addition method involves direct weight addition of fly ash to cement, replacing part of the aggregate in concrete, in order to achieve the correct yield. Partial replacement method involves replacement of a part of the Portland cement with excess weight of fly ash, replacing also part of the aggregate in order to achieve the correct yield. The third method is divided in itself into two as modified replacement method and rational proportioning method. In the modified replacement method, the fly ash content in the mixture is modified and it is shown that the strength of fly ash concrete at early stages becomes comparable to that of the control concrete. The results of the studies have shown that to get equal strength of the control concretes between 3 and 28 days old, the amount of added fly ash in concrete must be more than the amount of removed cement. The rational proportioning method was firstly proposed by Smith [12]. Smith modified conventional mixture proportioning methods by proposing a k efficiency factor. Smith reported that the weight of fly ash (F) is equivalent to cement with a weight of (kF), where k is a binding efficiency factor. The water/cementitous materials ratio is [$W/(C+kF)$] [13,14].

The literature is rich in publications regarding the effect of fly ash, especially of low-calcium fly ash, on concrete [3–5,15,16]. Papadakis and Tsimas [11] and Papadakis et al. [17] studied the efficiency factor and design of SCM in concrete and reported that when SCM replaced aggregates, higher strength values compared to the control mixtures were obtained. When SCM replaces cement, the strength was reduced. In order to estimate the k values, the following empirical equation (Eq. (1)) was used. Using the mean measured values of the compressive strength of the control specimen, the parameter K was estimated. The k values for the SCM concrete of the present work were calculated using Eq. (2). For fly ash, the k values are close to unity (Eq. (1)) at early ages:

$$f_c = K\left(\frac{1}{W/C} - a\right) \tag{1}$$

$$f_c = K\left(\frac{1}{W/(C+kP)} - a\right) \tag{2}$$

Papadakis also investigated low-calcium and high-calcium fly ash in Portland cement systems in other works [8,15]. It is reported that when aggregates are replaced by low-calcium fly ash, higher strengths are observed after 14 days; whereas in cement replacement, higher strengths are observed after 91 days. When aggregates are replaced by high-calcium fly ash, significantly higher strengths are observed from the beginning of the hydration, as well as higher water binding and significantly lower porosity. In the case of high calcium fly ash replacement of cement, the strength remained constant. The final strength gain is roughly proportional to the content of active silica in the mortar volume. Ganesh Babu and Rao [18] investigated the efficiency factor of fly ash in concrete, considering the strength to water/cement ratio relations, age, and percentage of replacement. It is reported that the overall cementing efficiency (k) of fly ash was established through a general efficiency factor (k_e) and percentage efficiency factor (k_p), which depends on the age and replacement percentage, respectively.

In this paper, an experimental investigation of optimum use of fly ash in concrete was carried out. The amount of fly ash with optimum efficiency was determined for concrete with various cement dosages. It was shown that fly ash/cement ratio is an important factor determining the efficiency of fly ash.

2. Experimental work

2.1. Materials

Both of the binding materials that were used in this study, including Portland cement and fly ash, were all manufactured in Turkey. Their chemical compositions and properties are presented in Table 1. CEM I 42.5 ordinary Portland cement was used according to European Standard EN 197-1 [19]. The fly ash was obtained from a power plant, Çatalağzı Thermal Power Station, Turkey. It contains low amounts of calcium and sulfate [20,21]. It is classified as Class F FA

Table 1
Chemical compositions (%) and properties of binding materials

Binder	Chemical compositions (%)										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI[a]	SS[b] (cm^2/g)	SG[c] (g/cm^3)
Cement	20.72	4.88	2.95	61.83	1.39	2.33	0.19	0.67	3.17	3513	3.10
Fly ash (FA)	57.55	25.16	6.50	2.10	2.50	0.19	0.66	3.65	1.66	3355	2.09

[a] Loss on ignition.
[b] Spesific surface.
[c] Spesific gravity.

because it is obtained from the combustion of bituminous coal [22]. Crushed limestone with a density of 2.70×10^3 kg/m^3, a maximum particle size of 12 mm, and a fineness modulus of 5.59 was used as the coarse aggregate. The fine aggregate was quartz sand and crushed limestone with a density of 2.68×10^3 kg/m^3 and a fineness modulus of 2.83. Volume percentages of fine and coarse aggregate were kept the same in all mixtures.

2.2. Specimen preparation and curing

A total of 28 mixtures with different recipes were prepared. 4 of them were prepared as control mixtures with 250, 300, 350, and 400 kg/m^3 cement content in order to calculate the Bolomey and Feret coefficients (K_B, K_F). Four groups of mixtures were prepared, each group containing six recipes and using the cement content of one of the control mixture as the base for the recipe. In each group 20% of the cement content of the control mixture was removed, resulting in starting mixtures with 200, 240, 280, and 320 kg/m^3 cement content. Fly ash in the amount of approximately 15%, 25%, 33%, 42%, 50%, and 58% of the rest of the cement content was added as partial cement replacement.

All mixtures had the same workability with a slump of 120 ± 10 mm. The main variable in the mixtures was the cementitious content and the water content. The mixture proportions of concrete are shown in Table 2. The raw

Table 2
Mix proportioning (kg/m^3) of concrete

Concrete	Mix proportioning (kg/m^3)					
	Cement	Fly ash	Water	CA[a]	FA[b]	Air content (%)
C250FA00	250	0	218	555	1285	1.6
C200FA30	200	30	216	558	1293	1.6
C200FA50	200	50	219	547	1266	1.8
C200FA65	200	65	221	538	1246	1.9
C200FA85	200	85	224	529	1225	1.8
C200FA100	200	100	229	519	1203	1.8
C200FA115	200	115	232	511	1184	1.7
C300FA00	300	0	225	536	1242	1.6
C240FA35	240	35	223	540	1251	1.6
C240FA60	240	60	225	527	1221	1.8
C240FA80	240	80	228	516	1195	1.9
C240FA100	240	100	231	508	1176	1.7
C240FA120	240	120	236	495	1146	1.8
C240FA140	240	140	240	484	1122	1.8
C350FA00	350	0	232	517	1197	1.7
C280FA40	280	40	230	522	1208	1.7
C280FA70	280	70	232	507	1174	1.8
C280FA95	280	95	236	493	1142	1.9
C280FA120	280	120	240	481	1114	1.8
C280FA140	280	140	245	470	1088	1.8
C280FA165	280	165	249	457	1058	1.8
C400FA00	400	0	239	498	1154	1.7
C320FA50	320	50	237	501	1159	1.8
C320FA80	320	80	240	484	1122	2.0
C320FA105	320	105	243	473	1096	2.0
C320FA135	320	135	247	458	1062	1.9
C320FA160	320	160	251	446	1032	1.9
C320FA185	320	185	255	436	1009	1.8

[a] Coarse aggregate.
[b] Fine aggregate.

Table 3
Workability (mm) and compressive strength (N/mm^2) of the concrete

Concrete	Workability	Compressive strength (N/mm^2)	
	Slump (mm)	28 days (N/mm^2)	180 days (N/mm^2)
C250FA00	12	23.1	26.6
C200FA30	12	21.3	25.0
C200FA50	11.5	22.4	26.7
C200FA65	11.5	22.9	27.2
C200FA85	12	22.7	27.1
C200FA100	12.5	21.4	25.7
C200FA115	12.5	20.0	24.2
C300FA00	12	29.5	34.2
C240FA35	12	27.1	32.2
C240FA60	11.5	29.2	34.6
C240FA80	11.5	29.6	35.3
C240FA100	12	29.8	35.6
C240FA120	12	28.5	34.2
C240FA140	12.5	26.9	32.6
C350FA00	12	35.7	41.4
C280FA40	11.5	33.0	38.9
C280FA70	12	35.6	42.2
C280FA95	11.5	36.2	43.3
C280FA120	12	36.5	43.4
C280FA140	12.5	35.5	42.5
C280FA165	12.5	33.6	40.8
C400FA00	12	41.5	48.0
C320FA50	11.5	39.3	46.3
C320FA80	11.5	41.4	49.3
C320FA105	11.5	42.5	50.7
C320FA135	12	42.7	50.9
C320FA160	12.5	41.2	49.7
C320FA185	12.5	39.5	48.3

materials of concrete were put in a forced mixer at the same time and were mixed for 3 min. The workability of fresh concrete including slump was measured right after the mixing was finished. The results are listed in Table 3. The mixture was cast into test specimens in mold by vibration at the temperature of 23±2 °C. The specimens were demolded after 1 day and then cured in water at a temperature of 20±2 °C. The test specimens were cured according to ASTM C192-88 [23].

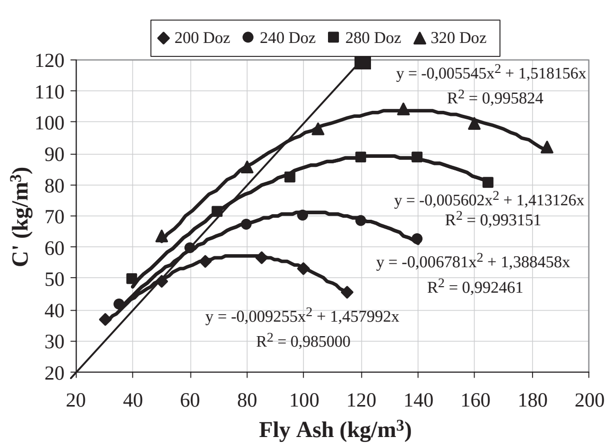

Fig. 1. The relation with equivalent cement content and used fly ash content at the age of 28 days for Bolomey equation.

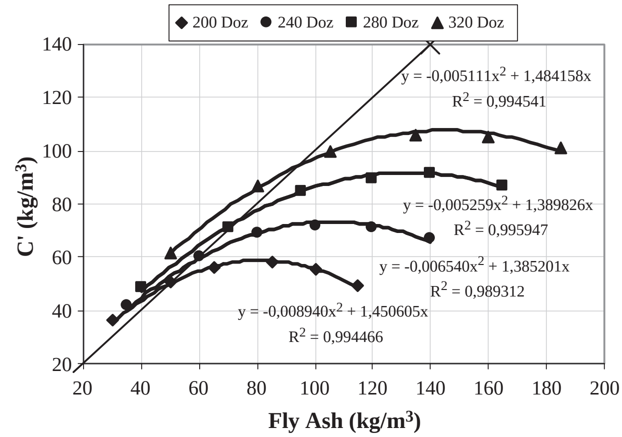

Fig. 2. The relation with equivalent cement content and used fly ash content at the age of 180 days for Bolomey equation.

2.3. Testing

The compressive strength of hardened concrete was measured. Cubic specimens of 15 cm were prepared for compressive strength test. For all results, the average of experimental results from three identical specimens was adopted. The compressive strength was tested according to BS 1881 [24]. At the age of 28 and 180 days, the specimens were taken out of water and tested for strength at a temperature of 23±2 °C.

3. Results and analyses

3.1. Compressive strength

The results of the compressive strength tests are given in Table 3. As it can clearly be seen from the data, for a given age and cement content, the compressive strength increases with increasing fly ash content up to a peak level and then decreases with further additions [25].

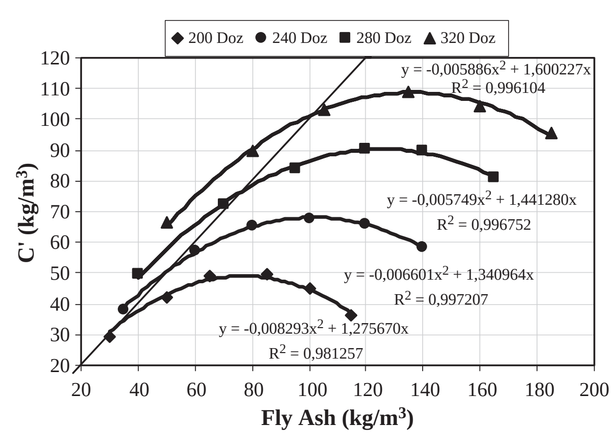

Fig. 3. The relation with equivalent cement content and used fly ash content at the age of 28 days for Feret equation.

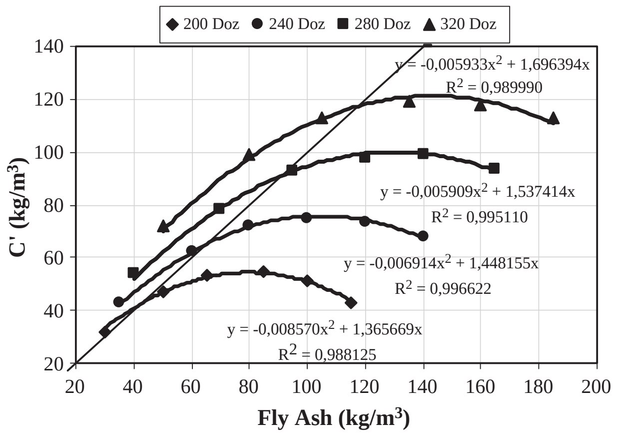

Fig. 4. The relation with equivalent cement content and used fly ash content at the age of 180 days for Feret equation.

3.2. Determination of optimum fly ash content

Bolomey and Feret strength equations have been used in order to determine the equivalent amount of cement for the optimum amount of fly ash. These are [26]:

$$f_c = K_B\left(\frac{C}{W+h} - a\right) \quad (3)$$

$$f_c = K_F\left(\frac{C}{c+w+h}\right)^2 \quad (4)$$

where K_B and K_F are the Bolomey and Feret coefficients, f_c is compressive strength of concrete (N/mm^2), C is cement content in concrete (kg/m^3), c is the amount of cement (absolute volume, m^3/m^3), W is the water content in concrete (kg/m^3), w is the amount of water (absolute volume, m^3/m^3), h is the air content in concrete (m^3/m^3), and a is a coefficient depending mainly on time and curing.

Initially, Bolomey (K_B) and Feret (K_F) coefficients have been calculated from the slopes of the lines obtained from the actual material contents of control mixtures and their 28-day and 180-day compressive strength values. The calculated coefficients were as follows: K_B=37,370 MPa (28 days) and 43,445 MPa (180 days), K_f=364,358 MPa (28 days) and 421,707 MPa (180 days). a in the Bolomey equation gives the best correlation with the values of 0.452 and 0.456 for 28 and 180 days, respectively.

Table 4
The optimum fly ash contents for 28-day and 180-day compressive strengths

Cement (dosage) (kg/m^3)	Optimum fly ash content for Bolomey equation (kg/m^3)		Optimum fly ash content for Feret equation (kg/m^3)	
	28 days	180 days	28 days	180 days
200	79	81	77	80
240	102	106	102	105
280	126	132	125	130
320	137	145	136	143

Equivalent cement contents C^1 and c^1 (i.e., the amount of cement that is needed to replace the fly ash in the fly ash mixed concrete in order to get the same experimental compressive strength) have been calculated using the Bolomey and Feret equations in the form presented in Eqs. (5) and (6). In these equations, C and c show the actual cement contents, and C^1 and c^1 are the equivalent (fictitious) cement content:

$$f_c = K_B\left(\frac{C+C^1}{W+h} - a\right) \quad (5)$$

$$f_c = K_F\left(\frac{c+c^1}{c+c^1+w+h}\right)^2 \quad (6)$$

Equivalent cement contents (C^1) and the relationship of the fly ash contents (F) used in test mixtures are obtained

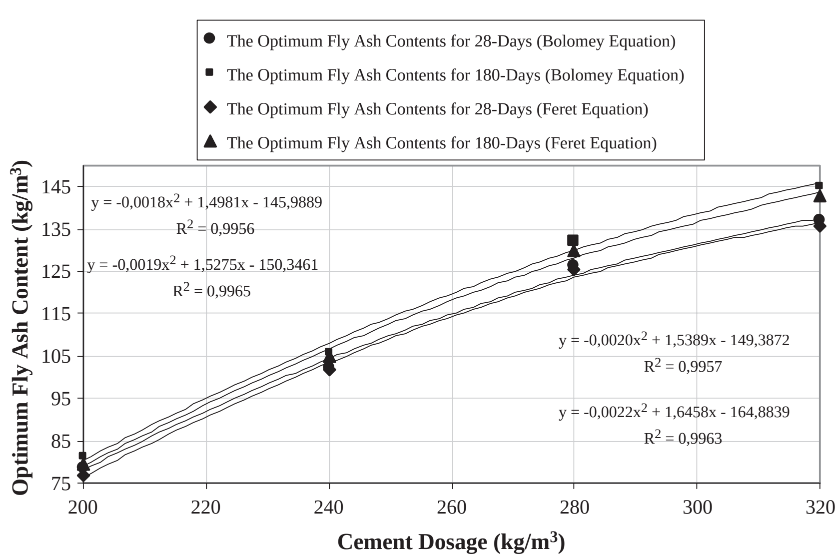

Fig. 5. The optimum fly ash contents at the age of 28 and 180 days compressive strengths (Bolomey and Feret equations).

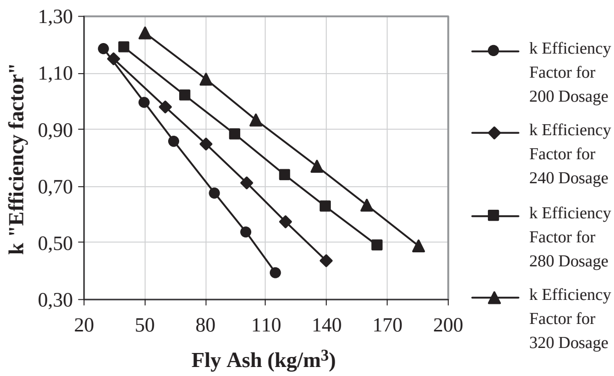

Fig. 6. The relation with efficiency factor and fly ash content at the age of 28 days for Bolomey equation.

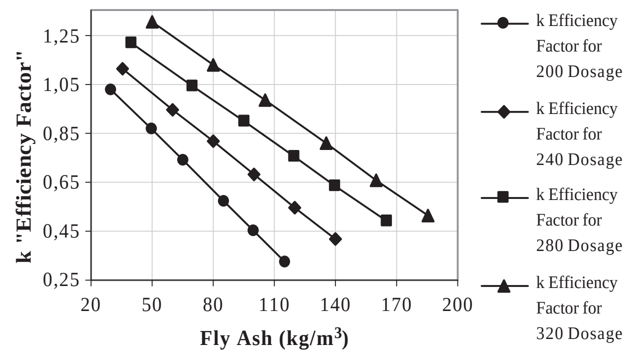

Fig. 8. The relation with efficiency factor and fly ash content at the age of 28 days for Feret equation.

separately for two equations and they are presented in Figs. 1–4. An equation of the form $C^1=aF^2+bF$, which passes from the origin and has a maximum, is used in order to determine the relationship between the equivalent cement content and the fly ash content. Each of the F parabolas, which are obtained by Bolomey and Feret equations, displays good correlations (Fig. 5).

The slopes of the lines drawn from any point of curves (C^1–F) to the origin give the efficiency of the fly ash replacement. The intersection of the curves with the ($C^1=F$) line gives the one unit fly ash in weight required to replace one unit cement in weight.

The peak points of C^1–F curves are obtained by taking the derivatives of these curves. It is clearly obvious that these points give the fly ash contents that correspond to the greatest compressive strengths. Up to the peak points, the effectiveness is high but the compressive strength is low. But beyond these peak points, both effectiveness and compressive strengths are lower. Hence these points show the maximum amounts of fly ash that can be used with optimum efficiency. The optimum efficiency values obtained from the experiment and then evaluation are shown in Table 4. In addition, the graph of efficiency factor k is shown in Figs. 6–9. It is seen in these graphs that as the amount of fly ash used for the same amount of cement increases, the efficiency of the fly ash gets lower.

4. Evaluation of the experimental results and discussion

The equations that represent the curves in Figs. 1–4 are of quadratic nature and the curves pass through the origin and have a maximum point. As it is seen from the graphs, they display a good agreement with the experimental results. This maximum point shows that even if the amount of fly ash increases, the equivalent cement amount starts to decrease after a certain point. This indicates that, from the compressive strength point of view, the fly ash is not used with sufficient efficiency, and that it acts as fine aggregate in the mixture rather than a cementitous additive and since all of it does not enter into reaction, it displays deficiency effect. When the curves are compared, it can be said that the same amount of fly ash in mixtures with different cement contents requires different amounts of efficient binding and this increases with the cement content.

As it is known, fly ash converts $Ca(OH)_2$, which is the hydration product of cement, into C–S–H. As the cement content in the concrete mixture increases, hydration product will also increase and hence the amount of $Ca(OH)_2$ with which the fly ash will enter into reaction will increase, then an increased amount of C–S–H will result. Consequently, in

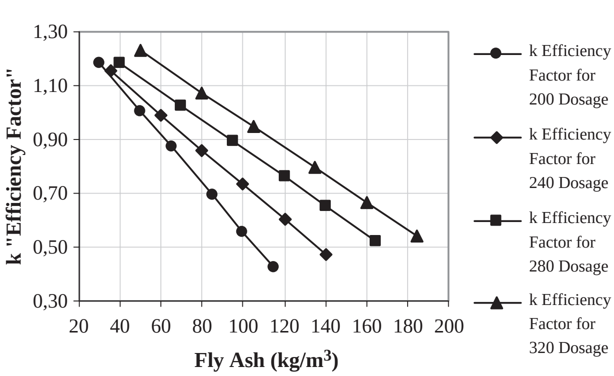

Fig. 7. The relation with efficiency factor and fly ash content at the age of 180 days for Bolomey equation.

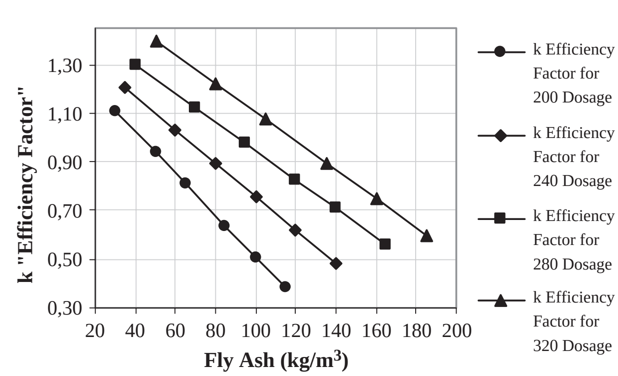

Fig. 9. The relation with efficiency factor and fly ash content at the age of 180 days for Feret equation.

this way, fly ash will be used more efficiently. The fact, that the curves decrease after a peak point, may be connected to the existence of extra fly ash in the medium, which cannot enter into reaction.

The points at which the C^1=F line cuts the curves indicate the points at which the amount of efficient binding is equal to the amount of fly ash used. At these points, fly ash behaves as an equivalent amount of cement. Fly ash contents which are equal to the amount of efficient binding will also increase as the cement content increases. This may also be connected to the amount of $Ca(OH)_2$. C^1–F curves that were obtained from Bolomey and Feret strength formulae conjure well with each other. This shows the reliability of the approach used in this study.

5. Conclusions

This study showed that strength increases with increasing amount of fly ash up to an optimum value, beyond which strength starts to decrease with further addition of fly ash. The optimum value of fly ash for the four test groups is about 40% of cement. Fly ash/cement ratio is an important factor determining the efficiency of fly ash.

As the cement content in the concrete mixture increases, hydration product $Ca(OH)_2$ will also increase and hence the amount of $Ca(OH)_2$ with which the fly ash will enter into reaction will increase, then an increased amount of C–S–H will result. Consequently, in this way, fly ash will be used more efficiently. C^1–F curves decrease after a maximum point, which may be connected to the existence of excess fly ash in the medium which cannot enter into reaction. This indicates that the fly ash which could not enter into the reaction behaves like fine aggregate.

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