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Efficiency factor of high calcium Class F fly ash in concrete

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Abstract. This paper studied the cement efficiency factor (*k* factor) of high calcium Class F fly ash. This *k* factor represents a unit of fly ash with efficiency equivalent to *k* unit of cement. The high calcium Class F fly ash was used to replace cement in concrete. The modified Bolomey's law with linear relationship was used for the analysis of the result of compressive strength, cement to water ratio (*c/w*) and fly ash to water ratio (*f/w*) by using the multi-linear regression to determine the *k* factor and other constants in the equations. The results of analysis were compared with the results from other researcher and showed that the *k* factor of high calcium Class F fly ash depends on the fineness of fly ash, replacement level and curing age. While the amount of CaO content in Class F fly ash not evident. Furthermore, necessary criteria and variables for the determination of the *k* factor including the use of the *k* factor in concrete mix design containing fly ash were proposed.

Keywords: efficiency factor; fly ash; Class F; concrete; multi-linear regression analysis.

1. Introduction

Fly ash is a by-product of coal-burning in power plants. It is widely used as a cementitious material and a pozzolanic ingredient in concrete. The use of fly ash in concrete is constantly increasing because it improves the properties of concrete, namely workability, durability, and long term strength in hardened concrete. Fly ash consists mainly of SiO_2, Al_2O_3, Fe_2O_3 and CaO and some impurities. According to ASTM C618 (2003), fly ash are specified in two major classes and are designated as Class F and Class C. Class F is fly ash normally produced from the burning of anthracite or bituminous coal and has the $SiO_2+Al_2O_3+Fe_2O_3$ content higher than 70%. Class C is fly ash normally produced from the burning of lignite or sub-bituminous coal with the $SiO_2+Al_2O_3+Fe_2O_3$ content higher than 50%. Usually, Class F fly ash has a low CaO content and exhibits pozzolanic properties. Class C fly ash, on the other hand, may contain higher than 10% CaO and exhibits both pozzolanic and cementitious properties. However, the variations in coal composition and combustion condition have significant effects on the heterogeneity of chemical and mineralogical compositions of fly ash. The Class F fly ash can also contain a high amount of CaO.

In Thailand, Mae Moh power plant in Lampang province produces around 3 million tons of lignite fly ash annually. The $SiO_2+Al_2O_3+Fe_2O_3$ content of this fly ash is usually higher than 70%.

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The CaO varies generally between 10-20%. It is being used quite extensively for construction in Thailand.

There are many methods for designing or predicting the behaviors of fly ash in mortar and concrete (Hwang and Hsieh 2007, Chakraverty *et al*. 2008, Rukzon and Chindaprasirt 2008). One specific method for strength predicting is known as the fly ash cementing efficiency factor concept proposed by Smith (1967). The efficiency factor (k) is defined as a number representing a part of the fly ash in concrete mixture which can be considered as equivalent to Portland cement. The equivalent fly ash produces concrete with the same properties as the concrete without fly ash (Ganesh Babu and Siva Nageswara Rao 1996, Papadakis and Tsimas 2002). From this concept, the term of water to cement ratio (w/c) of the conventional concrete without fly ash is adjusted to the equivalent water to cement ratio $(w/c)_{eq}$ for the fly ash concrete as shown in Eq. (1).

$$\left(\frac{w}{c}\right)_{eq} = \frac{w}{c+kf} \tag{1}$$

Where:
w = water content
c = Portland cement content
k = fly ash cementing efficiency factor
f = fly ash content

Many researchers in this field have considered the efficiency factor of various type of fly ash and others pozzolan. Ganesh Babu and Siva Nageswara Rao (1996) studied the efficiency factor of fly ash in concrete and found that the overall cementing factor (k) of fly ash could be established through a general efficiency factor (k_e) and percentage efficiency factor (k_p) depending on the testing age and amount of replacement, respectively. The BS EN 206 (2000) recommends that fly ash can be introduced as a pozzolanic addition in designed concrete mixture with an equivalent k = 0.2 or 0.4 depending on the cement class.

Papadakis and Tsimas (2002) and Papakadis *et al*. (2002) studied the efficiency factor of supplementary cementitious materials (SCM) such as silica fume, fly ash, slag, and natural pozzolan and reported that these values were valid for a content of SCM in concrete and depended on the concerned properties such as strength and durability. Oner *et al.* (2005) investigated the efficiency and the maximum Class F fly ash content for maximum compressive strength using Bolomey and Feret strength equation and showed that the optimum fly ash was about 40% of cement and fly ash/cement ratio was an important factor determining the efficiency of fly ash. Yamamoto *et al*. (2006) studied the pozzolanic reaction of Class F fly ash in mortar and found that the K-value from Feret's law is useful for the estimation of the degree of reaction. In addition, Tang (2010) studied the degree of pozzolanic reaction using factor in term α_p to replace the k factor and found that the degree of cement hydration in the blended cement pastes can be calculated.

In spite of all these investigations, there is still a lack of investigation on the efficiency of high calcium Class F fly ash. In this paper, an experimental investigation of efficiency factor of high calcium Class F Mae Moh fly ash in concrete was carried out using modified Bolomey's law. The mix proportions of concrete were designed at various compressive strengths. The amounts of fly ash were replaced of cement at rate of 0, 20, 40, and 60% by weight of binder. The compressive strengths of concrete were tested at the age of 14 and 28 days. An expression predicting compressive strength including the parameters mentioned above was proposed. In addition, the analysis results were compared to those of other researches.

2. Calculation of *k* factor

The famous formula that shows relationship between compressive strength of concrete and *w/c* ratio is Abrams' law (Abrams 1918) as follow

$$R = \frac{k_1}{(k_2)^x} \tag{2}$$

Where:
R = compressive strength of concrete
x = ratio between volume of water and volume of cement
k_1, k_2 = empirical constants for a given materials, age of curing and test conditions

In 1927, Bolomey (1927) proposed a linearized form Feret's formula as shown in Eq. (3). This gives the results very similar to Abrams' law.

$$R = p_1\left(\frac{1}{w/c} - p_2\right) \tag{3}$$

Where:
p_1, p_2 = empirical factor materials
c = cement content in concrete mixture
w = water content in concrete mixture

Hedegaard and Hansen (1992) suggested that strength development of fly ash concrete may be due to the hydration of cement and reaction of fly ash independent of pore-filler mechanism in the concrete. Therefore a linear relation between ordinary concrete compressive strength and cement to water ratio as shown in Eq. (4) can be expressed with fly ash cementing efficiency factor concept in term of a modified Bolomey's law as

$$\sigma_c = A_1\left(\frac{c}{w}\right) + A_3 \tag{4}$$

$$\sigma_c = A_1 + \frac{(c+kf)}{w} + A_3 = A_1\left(\frac{c}{w}\right) + A_1\left(\frac{kf}{w}\right) + A_3 \tag{5}$$

Then, it follows that

$$\sigma_c = A_1\left(\frac{c}{w}\right) + A_2\left(\frac{f}{w}\right) + A_3 \tag{6}$$

Hence

$$k = \frac{A_2}{A_1} \tag{7}$$

Where:
σ_C = compressive strength of concrete (MPa)
c = cement content in concrete mixture (kg/m^3)
w = water content in concrete mixture (kg/m^3)
f = fly ash content in concrete mixture (kg/m^3)
k = fly ash cementing efficiency factor
A_1, A_2, A_3 = empirical constants for a given materials, age of curing and test conditions.

3. Experimental programs

3.1 Materials

The materials used in this study consisted of Portland cement type I (PC), Lignite fly ash (FA) from the Mae Moh power station in northern Thailand, coarse and fine aggregates, and tap water.

Physical properties of materials are given in Table 1. The specific gravity of PC was 3.15 with Blaine fineness of 3580 cm^2/g. FA had 42.5% retained on a sieve No. 325 (opening 45 mm), specific gravity of 2.33, and Blaine fineness of 3045 cm^2/g. Local river sand with specific gravity of 2.67 and fineness modulus of 2.73 was used as fine aggregate and crushed limestone with a fineness modulus of 7.51 and specific gravity of 2.70 was used as coarse aggregate in concrete mixture.

Chemical compositions of PC and FA are listed in Table 2. The oxides of PC were CaO (62.7%), SiO_2 (21.5%), Al_2O_3 (4.5%), and Fe_2O_3 (3.1%) and SO_3 (3.5%). The loss on ignition (LOI) was 1.2%. FA was a high calcium Class F pozzolan according to ASTM C618-08a (2008) 74.8% of the sum SiO_2, Al_2O_3, and Fe_2O_3, 2.6% of SO_3, 16.6% of CaO and 0.1% of LOI.

3.2 Mixture proportions and testing

Four groups of main concrete mixtures were designed according to ACI 211 (2000). For all main mixtures, PC was replaced by FA at rates of 20, 40, and 60% by weight of binder. The mixture

Table 1 Physical property of materials

Properties	Portland cement type I	Fly ash	Fine aggregate	Coarse aggregate
– Specific gravity	3.15	2.33	2.67	2.70
– Absorption (%)	-	-	0.52	0.38
– Fineness modulus	-	-	2.73	7.51
– Retained on No. 325 sieve	-	42.4	-	-
– Blaine fineness (cm^2/g)	3580	3045	-	-

Table 2 Chemical composition of cement and fly ash

Oxides	Cement	Fly ash
SiO_2	21.5	38.7
Al_2O_3	4.5	20.8
Fe_2O_3	3.1	15.3
CaO	62.7	16.6
MgO	1.1	1.5
Na_2O	1.5	1.2
K_2O	0.7	2.7
SO_3	3.5	2.6
LOI	1.2	0.1
$SiO_2 + Al_2O_3 + Fe_2O_3$	-	74.8

Table 3 Concrete mix proportions

Symbol	Proportions (kg/m^3)					
	PC	FA	Water	Fine aggregate	Coarse aggregate	Slump (mm)
20PC	346	0	217	864	910	50
25PC	380	0	217	831	909	50
30PC	409	0	217	801	908	55
35PC	447	0	217	771	903	70
20PC20FA	299	75	206	863	907	70
25PC20FA	327	82	206	828	907	50
30PC20FA	355	89	206	797	897	50
35PC20FA	386	96	206	766	804	55
20PC40FA	242	161	192	865	909	50
25PC40FA	265	176	192	829	908	50
30PC40FA	287	191	192	797	903	50
35PC40FA	312	208	192	764	850	60
20PC60FA	182	272	182	851	895	75
25PC60FA	199	298	182	813	891	85
30PC60FA	215	323	182	780	883	65
35PC60FA	234	351	182	745	872	65

proportions of concrete and slumps of fresh concretes are listed Table 3.

The fresh concretes were prepared using a rotating drum mixer. The concrete specimens were cast in cubes of 150 mm. After casting for 24 h, the concrete samples were removed from the moulds and immersed in water at 23±2°C until testing. The compressive strengths of concretes were determined at 14 and 28 days. For each age, the average of experimental results from three specimens was reported.

4. Results and discussion

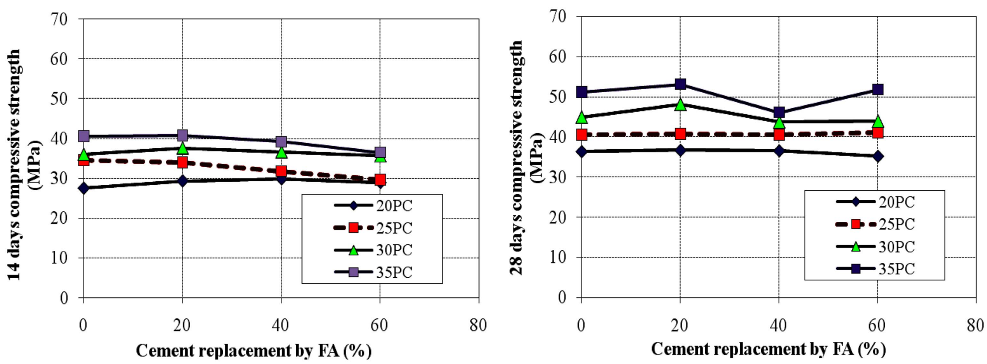
4.1 Compressive strength of concretes

Table 4 presents cement to binder ration (*w/b*), cement to water ratio (*c/w*), water to fly ash ratio (*f/w*), and compressive strengths of concretes. The 14 and 28 days compressive strengths varied from 27.5-40.8 MPa and 35.2-53.1 MPa, respectively. The mixes were designed to obtain similar slumps of 50-85 mm. Fig. 1 shows the relationship between compressive strength of concrete and FA replacement rate. The compressive strengths of fly ash concretes were approximately the same as those of normal concrete. This is due to reduction of water to binder ratio (*w/b*) of the mixes containing fly ash as a result of the ball bearing effect of the spherical FA particles. Additional pozzolanic reaction and the packing effect of the small fly ash particles contributed to the compressive strength development. The concretes with 20% cement replacement by FA give slightly higher compressive strength than those of 40 and 60% due to the small reduction in Portland cement.

Table 4 Compressive strengths

Symbol	*w/b* ratio	*c/w* ratio	*f/w* ratio	Compressive strength (MPa)	
				14 days	28 days
20PC	0.63	1.59	0.00	27.5	36.4
25PC	0.57	1.75	0.00	34.5	40.6
30PC	0.53	1.88	0.00	36.0	44.9
35PC	0.49	2.06	0.00	40.6	51.2
20PC20FA	0.55	1.45	0.36	29.3	36.7
25PC20FA	0.50	1.59	0.40	34.0	40.7
30PC20FA	0.46	1.72	0.43	37.6	48.1
35PC20FA	0.43	1.87	0.47	40.8	53.1
20PC40FA	0.48	1.26	0.84	29.8	36.6
25PC40FA	0.44	1.38	0.92	31.8	40.6
30PC40FA	0.40	1.49	0.99	36.6	43.7
35PC40FA	0.37	1.63	1.08	39.2	46.1
20PC60FA	0.40	1.00	1.49	28.9	35.2
25PC60FA	0.37	1.09	1.64	29.7	41.1
30PC60FA	0.34	1.18	1.77	35.6	43.9
35PC60FA	0.31	1.29	1.93	36.5	51.8

Note: *w* = water, *b* = binder (cement + fly ash), *c* = cement, *f* = fly ash.



(a) 14 days (b) 28 days

Fig. 1 Variation of compressive strength with replacement of FA

4.2 Determination of k factor

In this study, the *c/w* ratio, and *f/w* ratio varied between 1.00 to 2.06, and 0 to 1.93, respectively. The combination of *c/w* ratio and f/*w* ratio of 16 concrete mixes are showed in Fig. 2. The graph indicated a good coverage of the tests. From the Eq. (6), a multi-linear regression analysis based on least squares method was applied to obtain the relationship between *c/w* ratio, *f/w* ratio, and compressive strength as well as to calculate the constants A_1, A_2 and A_3 at each age. The results at the age of 14 and 28 days based on the compressive strength of 16 mixes are shown in Eqs. (8) and

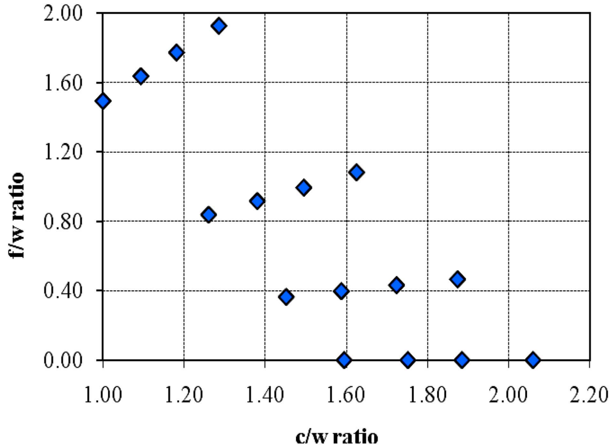


Fig. 2 The combinations of *c/w* and *f/w* ratios of concretes in this study

(9). The correlation coefficient (R^2) of 0.92 and 0.93 indicates the goodness of fit. To further examine how well the developed model fits the tested data, the predicted values from Eqs. (8) and (9) versus experimental compressive strengths at 14 and 28 days were plotted as shown in Fig. 2. The predicted data were within the line of ±10% of experimental values. The modified Bolomey equation (Eq. (6)), therefore, accurately predicts the compressive strengths. Therefore, the present model is expected to provide a good level for compressive strength estimate of high calcium Class F fly ash concrete.

$$\sigma_c(14D) = 23.53\frac{c}{w} + 8.01\frac{f}{w} - 7.56, \quad R^2 = 0.92 \tag{8}$$

$$\sigma_c(28D) = 32.32\frac{c}{w} + 12.26\frac{f}{w} - 13.96, \quad R^2 = 0.93 \tag{9}$$

From Eqs. (8) and (9), the *k* factor of fly ash at 14 and 28 days can be obtained as;

$$k(14D) = \left(\frac{A_2}{A_1}\right)_{14} = \frac{8.01}{23.53} = 0.34 \tag{10}$$

$$k(28D) = \left(\frac{A_2}{A_1}\right)_{28} = \frac{12.26}{32.32} = 0.38 \tag{11}$$

The results show that the *k* factors of fly ash at 14 and 28 days are 0.34 and 0.38, respectively. The *k* factor tends to increase with age of concrete owing mainly to the pozzolanic reaction. Thus, it is essential that fly ash concrete requires prolonged curing (Bharatkumar *et al*. 2001). This result agrees with the experimental of Rajamane *et al.* (2007) which showed that the *k* factors of Class F fly ash when used as a partial replacement for both Portland cement and fine aggregate increased with the age of concrete.

Table 5 summarizes the replacement rate, the constants A_1, A_2 and A_3, R^2, and *k* factors of fly ash at the age of 14 and 28 days. The *k* factors of fly ash varied from 0.49-0.35 and 0.50-0.39 for fly ash replacement levels of 20-60% at the age of 14 and 28 days, respectively. The factor decreased slightly with the increasing level of replacement as shown in Fig. 4. The level of replacement of fly ash is an important factor determining the efficiency factor (Oner *et al.* 2005). From the above

Table 5 Results of the multi-linear regression analysis of this experimental data

Age of curing	Fly ash replacement (%)	A_1	A_2	A_3	R^2	$k = A_2/A_1$
14	0-60	23.53	8.01	-7.56	0.92	0.34
28	0-60	32.32	12.26	-13.96	0.93	0.38
14	20	24.46	11.36	-11.24	0.96	0.46
	40	23.14	8.83	-8.77	0.95	0.38
	60	22.21	7.67	-7.04	0.91	0.35
28	20	32.63	16.18	-17.87	0.99	0.50
	40	25.61	8.44	-4.89	0.96	0.33
	60	31.87	12.55	-16.39	0.99	0.39

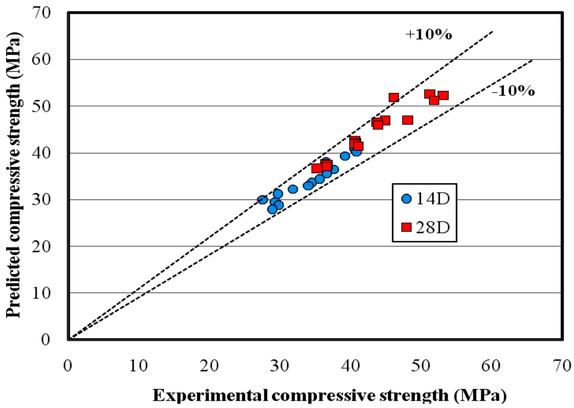


Fig. 3 Relationship between experimental and predicted compressive strength

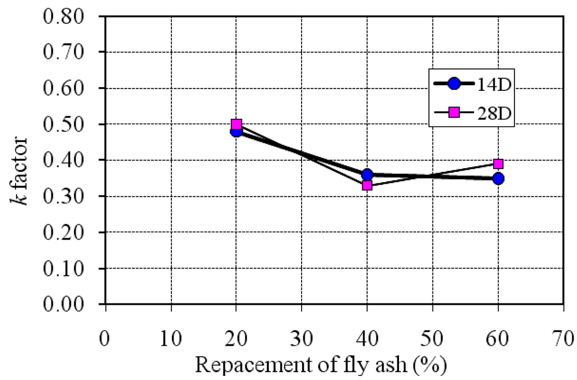


Fig. 4 Variation of level of fly ass replacement with *k* factor

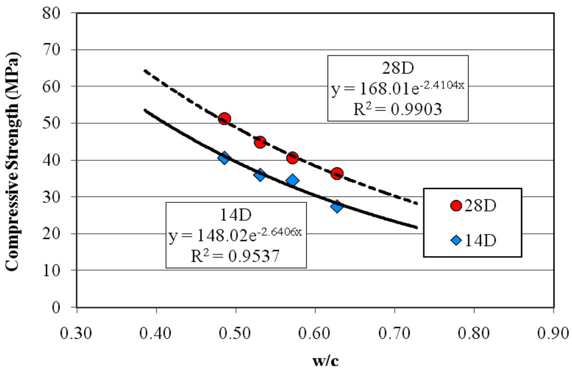


Fig. 5 Variation of compressive strength with *w/c* of normal concrete with out fly ash

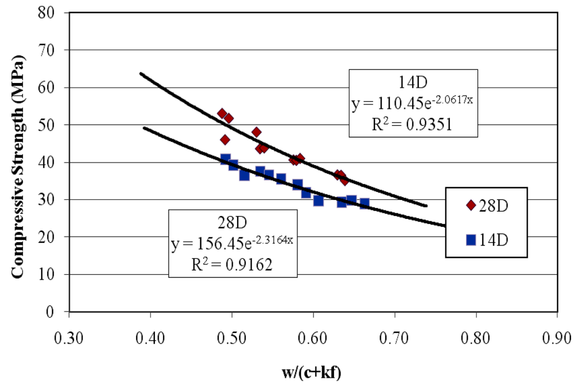


Fig. 6 Variation of compressive strength with *w/(c+kf)* of fly ash concrete

results, it can be recognized that *k* factor depend on both age of curing and level of replacement.

Fig. 5 shows the normal relationship between the compressive strength of normal concrete at 14 and 28 days with *w/c* ratio. For the fly ash concrete, the *w/b* and compressive strength relations had to be modified to give a good fit with the aid of *k* factor. The plot of compressive strength of fly ash concrete at 14 and 28 days with *w/(c+kf)* shown in Fig. 6 gave similar relationship to those of *w/c* to compressive strength relations of normal concrete. Therefore, test results indicated that the compressive strength of high calcium Class F fly ash concrete can be predicted using *k* factor concept, which was based on modified Bolomey equation.

4.3 Comparison of k factor of concrete from other researches

In order to compare the *k* factors of Class F fly ash concretes from the other researches, the compressive strength data of concretes containing Class F fly ash with various CaO contents were used for the comparison. The details of concrete and the multi-linear regression analysis results are presented in Table 6. The CaO contents of the Class F fly ashes varied between 2.1-16.6% and the Blaine fineness ranged from 2208-6645 cm^2/g. The range of slump of fresh concrete of 3.0-12.5 cm. was selected. From the multi-linear regression analysis with *c/w* between 0.2 and 2.9, *f/w* between 0-2.0, the *k* factors of fly ash were found to be between 0.09-0.86 and the R^2 of analysis results at each data ranged from 0.90-0.99 indicating good correlations of result obtained from Eq. (6). However, the *k* factor depends on various properties of fly ash and concrete.

The plot of the *k* factor and age of curing with fly ash of similar fineness as shown in Fig. 7 indicated that *k* factors increase with curing ages. For example, the *k* factor of fly ash with Blaine

Table 6 The general details of concretes evaluated and results of references data comparison with this study

References	Fly ash			Cement Replacement (%)	Range of		Slump (cm)	Results		
	Source	Class F (% CaO)	Fineness (cm^2/g)		*c/w*	*f/w*		R^2	*k*	Curing (days)
Slanicka (1990)	Czech Slovakia	2.8	5327	0-30	1.2-2.5	0.0-1.1	8.5-10	0.98	0.86	28
		3.1	2208	0-29	1.2-2.5	0.0-0.6	8.5-10	0.99	0.09	28
Hedegaard and Hasen (1992)	Asnaes (Denmark)	3.2	-	0-91	0.2-2.6	0.0-2.0	3-9	0.96	0.21	28
	Try (Denmark)	2.8	-	0-91	0.2-2.6	0.0-2.0	3-9	0.98	0.22	28
Oner *et al.* (2005)	Turkey	2.1	3355	0-37	0.9-1.7	0.0-0.7	11-12.5	0.90 0.90	0.48 0.54	28 180
Boonlualoah (2001)	Mae Moh (Thailand)	9.6	3233	0-60	0.5-2.9	0-1.7	8-10	0.95	0.42	28
Songpiriyakij (2002)	Mae Moh (Thailand)	9.0	6645	0-60	0.6-2.5	0.0-1.5	-	0.96	0.62	28
		11.3	3485	0-60	0.6-2.5	0.0-1.5	-	0.98 0.97 0.96 0.94	0.44 0.48 0.58 0.62	7 28 90 180
		10.1	2665	0-60	0.6-2.5	0.0-1.5	-	0.98	0.21	28
This study	Mae Moh (Thailand)	16.6	3045	0-60	1.0-2.1	0.0-1.9	5-8.5	0.92 0.93	0.34 0.38	14 28

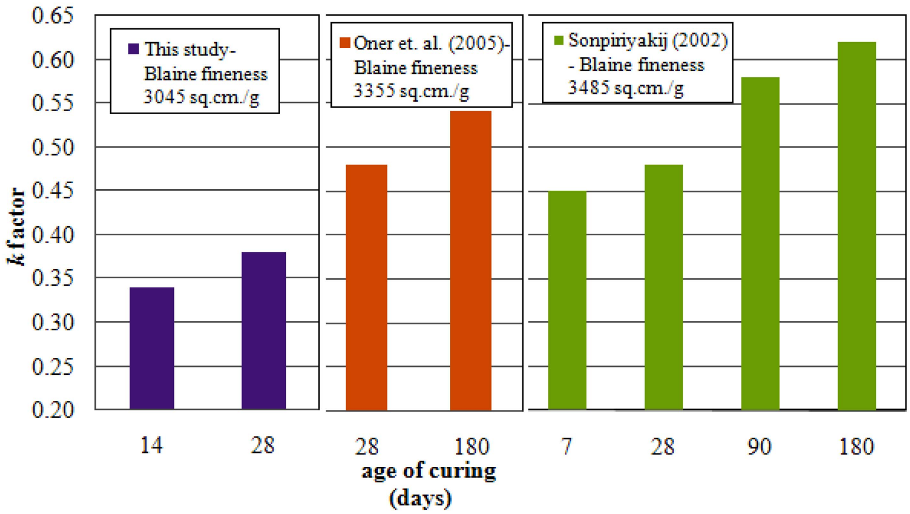


Fig. 7 Relationship between *k* factor of fly ash and age of curing

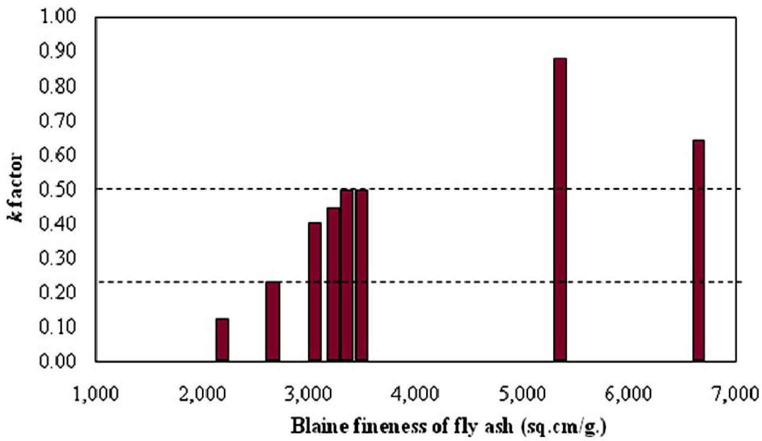


Fig. 8 Variation of *k* factor of fly ash at 28 days with various fly ash finenesses

fineness of 3485 cm^2/g (Songpiriyakij 2002) at 7, 28, 90, and 180 days were 0.44, 0.48, 0.58, and 0.62 respectively. The *k* factor of fly ash with Blaine fineness of 3355 cm^2/g (Oner *et al.* 2002) at 28 and 180 days were 0.48 and 0.54 respectively. These results conforms with the tested results (Blaine fineness of 3045 cm^2/g) which showed the *k* factor of high calcium Class F fly ash was 0.34 at the age of 14 days and increased to 0.38 at the age of 28 days. The *k* factor of fly ash improved with age as a result of the pozzolanic reaction.

Comparison the *k* factor and age of curing using various literatures data as shown in Fig. 7 showed that besides the age of curing, the *k* factor depends on fineness of fly ash. The plot of *k* factor of fly ash at the age of 28 days with various Blaine finenesses is shown in Fig. 8.

The *k* factor increases with the increase in the fineness. At the low fineness of 2208-2665 cm^2/g, the *k* factors were between 0.09-0.21. For the medium finenesses of 3045-3485 cm^2/g, the *k* factors were between 0.38-0.48. For the high fineness of 5327 and 6645 cm^2/g, the *k* factors were 0.86 and

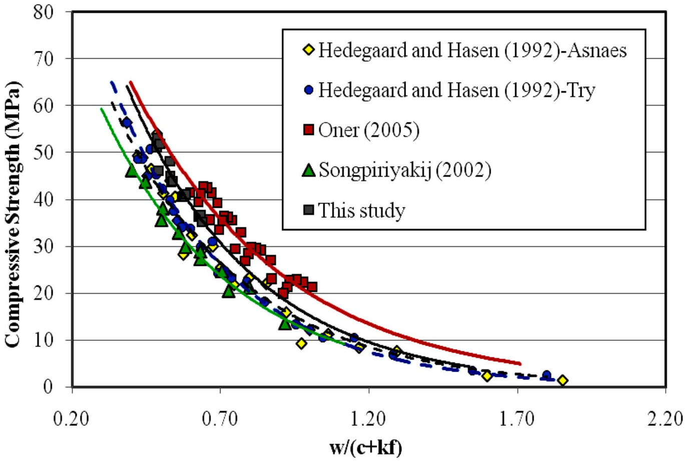


Fig. 9 Variation of compressive strength with *w*/(*c*+*kf*) of fly ash concrete at 28 days

0.62. The increasing of *k* factor with fineness of fly ash is due a higher pozzolanic reaction from a higher surface area of fly ash particle and a small fly ash particle that filled the voids (Chindaprasirt *et al*. 2005). In addition, Yamamoto *et al*. (2006) also found that all types of fine fly ash (CaO amount up to 8.4%) with high fineness showed higher *k* factor, and also suggested the linear relationship between gaining rate of *k* factor and logarithmic time.

From the 28 day *k* factor of this study, the variation of compressive strength with *w*/(*c*+*kf*) ratio of fly as concrete were plotted compare with various references data in Fig. 9. This shows that the high calcium Class F fly ash concretes can be represented by the compressive strength and the *w*/(*c*+*kf*) ratio similar to the other Class F fly ash with various amount of CaO.

For fly ashes of similar fineness with different CaO contents, the effect of CaO content is not observable. The *k* factors at the age of 28 days of fly ashes with CaO content of 2.1% and fineness of 3355 cm^2/g; CaO content of 11.3% and fineness of 3485 cm^2/g; and CaO content of 16.6% and fineness of 3045 cm^2/g were 0.48, 0.48 and 0.38, respectively. Although, the high CaO content gave low *k* factor of 0.38, this may be the results of the fineness and the experimental variation. This aspect needs further research and clarification.

For Mae Moh high calcium Class F fly ash in Thailand, the 28 days *k* factor varied from 0.38 to 0.62 depending on the fly ash fineness. However for the design purpose, it can be recommended that the *k* factor should be 0.30-0.60 for fly ash replacement between 20-60%.

5. Conclusions

In this experimental, the cement efficiency factor (*k* factor) of high calcium Class F fly ash was tested. The modified Bolomey's law with linear relationship was used for the analysis of the result of compressive strength of concrete, cement to water ratio (*c/w*), and fly ash to water ratio (*f/w*) by using the multi-linear regression to determine the *k* factor and other constants in the equations. In addition, the results were compared with those of Class F fly ash concretes of other researches. Based on the above results and discussions, the conclusions can be listed as follow.

1. The *k* factor concept is suitable for high calcium Class F fly ash. It is useful for estimating the

degree of the pozzolanic activity of high calcium Class fly ash and compressive strength of concrete.

2. The *k* factor of Class F fly ash depends on the characteristics of fly ash and concrete. The important factors are fly ash fineness, age of curing and replacement level. While the effect of the CaO content in Class F fly ash on *k* factor is small and inconclusive. This subject needs further i3. nvestigation.

3. Finally, for the design of high calcium Class F Mae Moh fly ash concrete, it is recommended that the *k* factor should be about 0.30 to 0.60 for fly ash replacement between 20-60% depending on the fly ash fineness.

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