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A study of ground coarse fly ashes with different finenesses from various sources as pozzolanic materials

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Abstract

The aim of this study is to evaluate the properties of ground coarse fly ashes, from five sources in Thailand, the shapes, sizes, and chemical compositions of which are completely different. Coarse fly ash was fractionated by an air classifier and ground into three different finenesses ranging from median particle sizes of 1.9–17.2 μm. Physical and chemical properties of the Portland cement and the fly ashes were investigated. Mortar cubes of 5 cm were cast with 20% replacement by weight of Portland cement with ground coarse fly ash. The compressive strengths of the fly ash–cement mortars were determined and compared with the control mortar. The results revealed that the degree of pozzolanic reaction, as determined using compressive strength, of coarse fly ash increased when its fineness was increased by grinding. The strength activity indices of the original fly ash–cement mortars at the curing ages of 7 and 28 days were in the range of 69–82% and 76–90%, respectively. When the particle size smaller than 9 μm of ground coarse fly ash was used, the strength activity index achieved was over 100% of that of the control within 28 days. The results also showed that the fineness of fly ash, not the chemical composition, was the major factor affecting the strength activity index of ground coarse fly ash–cement mortar.

Keywords: Ground coarse fly ash; Strength activity index; Fineness; Pozzolanic material

1. Introduction

Before 1997, fly ash from lignite coal had been used very little in Thailand, but in the following year, more than 300,000 tons of fly ash were utilized in ready mixed concrete for the construction of various structures including power plants, buildings, and infrastructures. Nevertheless, most engineers still have limited knowledge of the way in which fly ash influences the properties of concrete.

One disadvantage of using fly ash in concrete work is the slow development of the early compressive strength. Mehta [1] observed 11 fly ashes from different sources in the US and found that the calcium content and particle size distribution were the most important parameters governing the strength development rate. Swamy et al. [2] developed many mixes of normal and lightweight concretes containing 30% of fly ash by weight of cement which provided adequate early compressive strength compared to the concrete without fly ash; however, superplasticizer was employed in the study. Malhotra and Painter [3] also used superplasticizer to reduce the water to binder ratio, in order to improve the early compressive strength of fly ash concrete, and the results confirmed those of Swamy et al. [2]. Naik and Ramme [4] provided concrete mixes containing large quantities of fly ash which achieved compressive strengths of 21 and 28 MPa within 28 days. Their technique was to increase the binder content of the concrete, and as a result, the water to binder ratio could be reduced while still maintaining the target workability as well as achieving the target compressive strength. However, with the high degree of fly ash replacement, low early compressive strength was still a problem.

Slanicka [5] and Paya' et al. [6] separated fly ash into various finenesses and showed that the concrete with finer fraction of fly ash gave a better compressive strength than that without fly ash and the one with coarser fly ash reduced the compressive strength of concrete. Erdogdu and Turker [7] also found similar results in high lime fly ash. Therefore, the coarse fraction of fly ash seems to be unsuitable for the structural

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concrete work. Berry et al. [8] suggested that coarse fly ash exhibited low pozzolanic activity since it contained a high proportion of crystalline phases and thus should not be used in concrete.

It has been demonstrated that the compressive strength of concrete with fly ash can be improved by grinding the fly ash [9,10]. Although fractionation is much more cost effective in achieving small particle size fly ash than grinding, the residue from the classifying process still has to be disposed of. There is still no clear picture whether the coarse fraction of fly ash can engage in a pozzolanic reaction. The purpose of this study is to find out whether the pozzolanic activity of coarse fly ash can be improved by grinding.

2. Experimental program

2.1. Materials

The major materials used in this investigation consisted of Portland cement type I, river sand, and fly ash.

Fly ashes obtained from five different power plants in Thailand were used in this study. They were lignite fly ash from Mae Moh power plant at Lumpang province, designated as FM, sub-bituminous fly ashes from Rayong and Samutsakorn provinces, designated as FR and FS, respectively, and anthracite fly ash from Kanchanaburi province, designated as FK. All of these fly ashes were collected in June 1998. In addition, a fly ash more than three years old from an unidentified coal, designated as FN, was also studied. It should be noted that only FM was a by-product from coal in Thailand, the rest were by-products from imported coals.

In this study only coarse fractions of each fly ash were used in the investigation and they were ground into three different finenesses using a ball mill. The abbreviations L, M, S, and O were used to identify the fineness of fly ash as large, medium, small, and original (as received from silo), respectively. The refinement and seperation process is shown schematically in Fig. 1. It should be noted that after the first round of fractionating the fly ashes, using air classifier, the coarse fraction had a very large particle size ranging between 50% and 100% remaining on sieve No. 325 which exceeded the allowance of 34% as prescribed by ASTM C 618.

2.2. Material properties

The physical and chemical properties of the fly ashes and Portland cement type I were investigated. The fly ash particle morphologies were recorded using a scanning electron microscope (SEM). The specific gravity, the retention on sieve No. 325, and the Blaine fineness were tested in accordance with ASTM C 188, C 430, and C 204, respectively. Chemical composition was determined using X-ray Fluorescence Spectrometer.

2.3. Test of fly ash–cement mixture

Normal consistency and setting times of cement and fly ash–cement pastes containing 20% of fly ash by weight of cementitious material were tested as prescribed by ASTM C 187 and C 191, respectively.

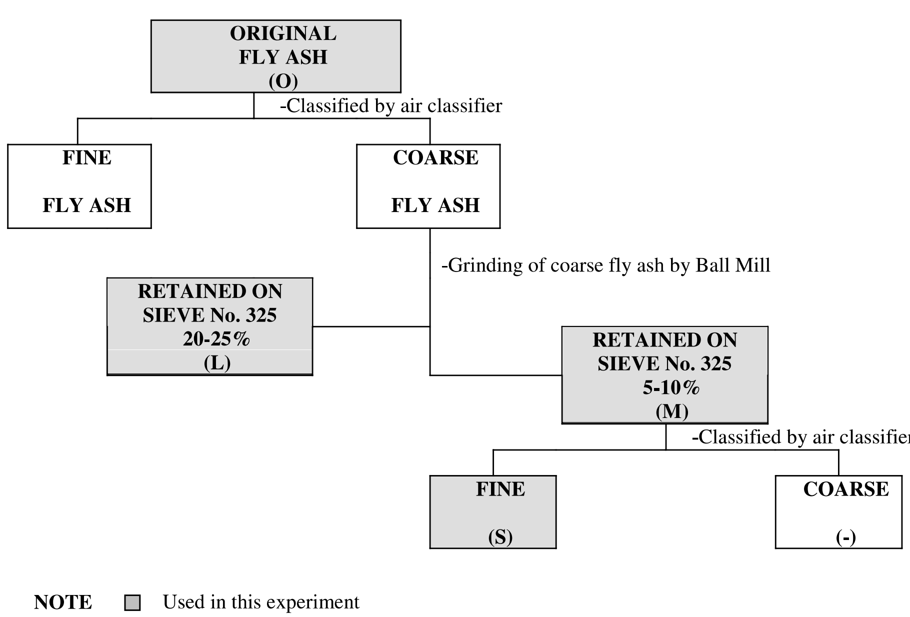

Fig. 1. Schematic process of ground coarse fly ash.

Standard 5-cm mortar cubes were prepared to determine compressive strengths at curing ages of 3, 7, 14, 28, 60, and 90 days. The specimens were immersed in water at room temperature after being removed from the molds. Portland cement type I was replaced by 20% of fly ash by weight and a binder to sand ratio of 1–2.75 was employed. A standard flow of 110 ± 5, specified by ASTM C 109, of all mortars was maintained by adjusting the quantity of mixing water.

3. Results and discussion

3.1. Fineness and particle shape

Table 1 shows the physical properties of the cement and the ground coarse fly ashes with different finenesses. The results of particle size analysis are shown in Fig. 2 and their median particle sizes are tabulated in Table 1. Surprisingly, fly ash FK-O showed a very high Blaine fineness of 7720 cm^2/g while it retained 45.9% on sieve No. 325 and the median particle size was 44.2 μm. This could be explained that its shape characteristic was spongy (irregular and porous), as shown in Fig. 3, which had high surface area. Therefore, only Blaine fineness may not be sufficient to indicate the fineness of fly ash especially for fly ash with spongy shape. Normally, fly ash is molten at a temperature of about 1500°C when it forms spherically shaped particles. If the burning temperature is lower than 1500°C, fly ash fails to melt and irregular particles are formed [11]. It was reported that spongy particle associates with partly burnt fragments of coal (carbon) resulting from incomplete combustion [12]; however, the LOI of FK-O is only 3.12%.

Table 1
Specific gravity, fineness, and median particle size of Portland cement type I and fly ashes

Sample type	Specific gravity	Retained on sieve No. 325 (%)	Blaine fineness (cm^2/g)	Median particle size (μm)
Cement	3.14	4.7	3120	13.0
FM-O	*2.02*	*37.4*	*2370*	*28.5*
FM-L	2.66	21.7	4630	9.0
FM-M	2.66	7.4	5670	5.3
FM-S	2.63	0.4	10260	1.9
FR-O	*2.19*	*32.9*	*3380*	*32.0*
FR-L	2.47	23.3	4620	15.4
FR-M	2.58	11.0	5970	10.5
FR-S	2.54	1.3	9590	4.7
FS-O	*2.24*	*17.8*	*5380*	*18.3*
FS-L	2.38	20.1	5150	17.2
FS-M	2.44	7.6	6320	11.7
FS-S	2.40	0.4	10040	5.3
FK-O	*2.50*	*45.9*	*7720*	*44.2*
FK-L	2.57	23.5	7430	10.5
FK-M	2.62	8.9	8910	4.8
FK-S	2.60	3.5	12330	3.7
FN-O	*2.23*	*26.9*	*4880*	*27.0*
FN-L	2.41	19.1	6320	13.7
FN-M	2.49	6.8	7880	7.8
FN-S	2.45	0.7	10190	4.2

3.2. Chemical compositions

The chemical compositions of the fly ashes and the Portland cement type I were analyzed using an X-ray Fluorescence Spectrometer and are tabulated in Table 2. The amount of CaO of the original fly ash varied between 1.03% and 8.36%. However, all fly ashes were classified into Class F as prescribed by ASTM C 618 since the sums of the major components SiO_2, Al_2O_3, and Fe_2O_3 were over 70%. The loss on ignition (LOI) of fly ash FS was 7.52% and exceeded the limitation of 6% as specified by ASTM C 618.

Many reports [7,8,10,13] conclude that classifying and grinding do not have much effect on the chemical composition of fly ash. The finer fly ash obtained by classifying may contain higher SO_3 and LOI than the original; however, the increase in LOI has no relation to the increase of carbon content of classified fly ash [8]. In recent papers [7,14], it was reported that the coarse fraction of fly ash had less SO_3 than the fine one. It may be an advantage to use ground coarse fly ash as cement replacement since SO_3 may be harmful to mortar or concrete durability.

3.3. Setting times

Table 3 shows the normal consistencies and setting times of Portland cement type I and the fly ash–cement pastes. The normal consistency value for cement paste was 24.7% while the value for paste with FM-O was 23.4%. However, pastes with fly ashes FR-O, FS-O, FK-O, and FN-O required more water resulting in higher normal consistency values. The initial and final setting times of cement pastes were 107 and 175 min, respectively, while pastes with fly ash tended to have longer setting times. However, when the fineness of each fly ash was increased, the setting times were gradually reduced. It should be noted that the setting times of all fly ash–cement pastes were within the limit specified by ASTM C 150.

3.4. Water requirement

The water to binder ratios to produce a standard flow of 110 ± 5 for all mortars are shown in Table 4 together with the water requirement values. The mortars made with original fly ashes FR-O, FS-O, FK-O, and FN-O required more water than that of the standard mortar

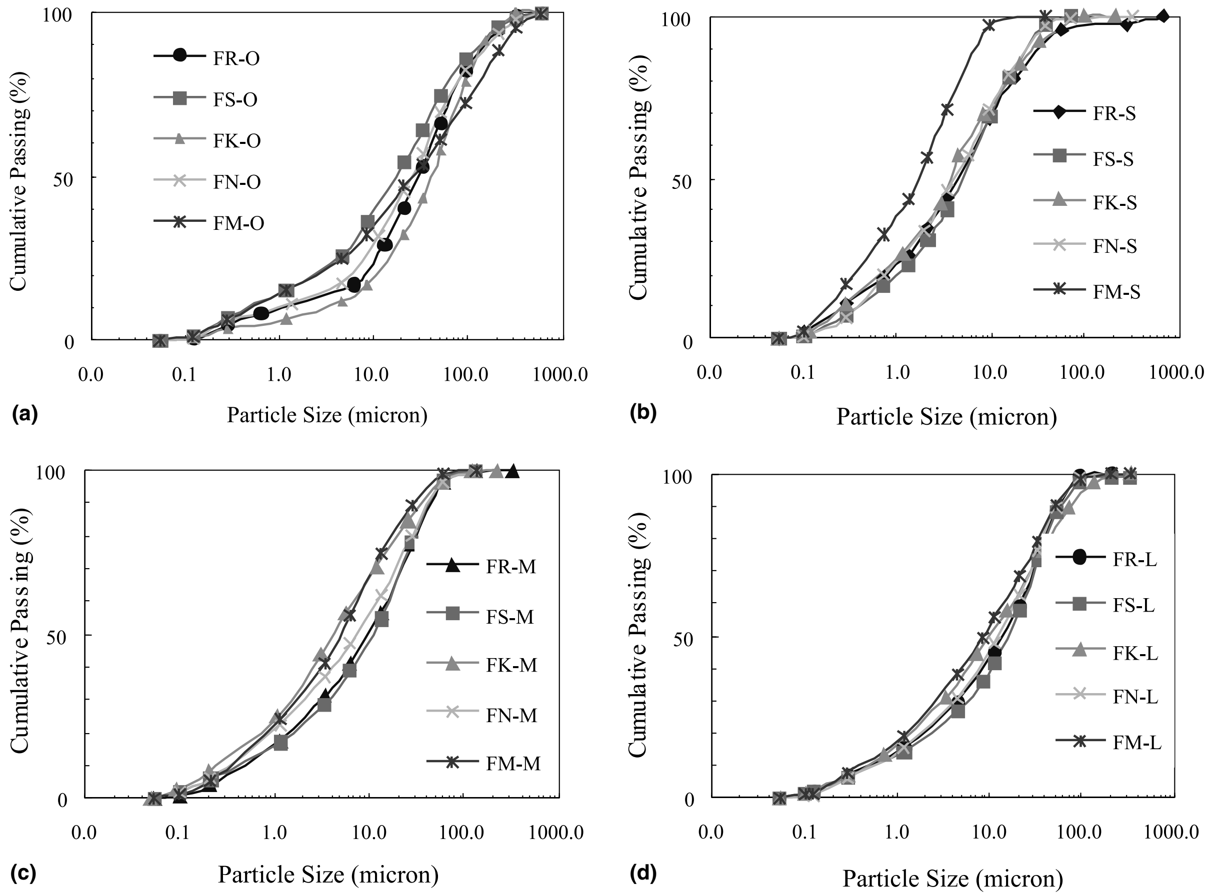

Fig. 2. Particle size distribution of fly ashes using Mastersizer S, Malvern Instruments. (a) Original particle size of fly ashes. (b) Small particle size of fly ashes. (c) Medium particle size of fly ashes. (d) Large particle size of fly ashes.

(104%, 101%, 106%, and 103%, respectively) except for FM-O (99%). This implied that fly ashes did not always improve the workability of mortar or concrete; moreover, mortar FK-O required water higher than 105% which was the limitation specified by ASTM C 618. Fly ashes FK-O and FS-O had irregular shape and porous particles (see Fig. 3) and thus needed more water to maintain the same flow as that of the standard mortar. The ground coarse fly ashes, having the irregular shape, did not show significant improvement of water requirement of mortar. However, the increase in fineness of ground coarse fly ashes resulted in slight decrease of water requirement. This is due to the increase in surface area (high water required) and the decrease of porous particles (low water required) of fly ash.

3.5. Compressive strength of mortar

The compressive strengths of standard mortar and mortars containing fly ashes are presented in Table 4. The water to binder ratio was varied between 0.67 and 0.73 in order to control the flow of mortar within the range of $110 \pm 5\%$.

At the age of 3 days, the compressive strengths of original fly ash–cement mortars were less than that of the standard mortar. For example, the compressive strength of standard mortar was 18 MPa compared with 13.5 MPa of the mortar FM-O, even though, the $W/(C+F)$ of both mortars were almost the same. However, when fly ash was processed, the rate of strength gain of mortars was improved significantly with the increase of fineness. With different kinds of fly ash, the rates of strength development were not the same (see Table 4).

At 90 days, the compressive strength of standard mortar was 35.8 MPa while the compressive strengths of the fly ash–cement mortars were between 28.3 and 43.5 MPa. It was noted that some fly ash–cement mortars still gave lower compressive strengths than that of the standard.

Considering the small particle size groups of ground coarse fly ashes in Fig. 2, the particle size distributions were almost the same. Mortars FR-S, FS-S, and FN-S, had the same $W/(C+F)$ of 0.68. These results revealed that the strength development rates were also the same as shown in Fig. 4 even though their chemical

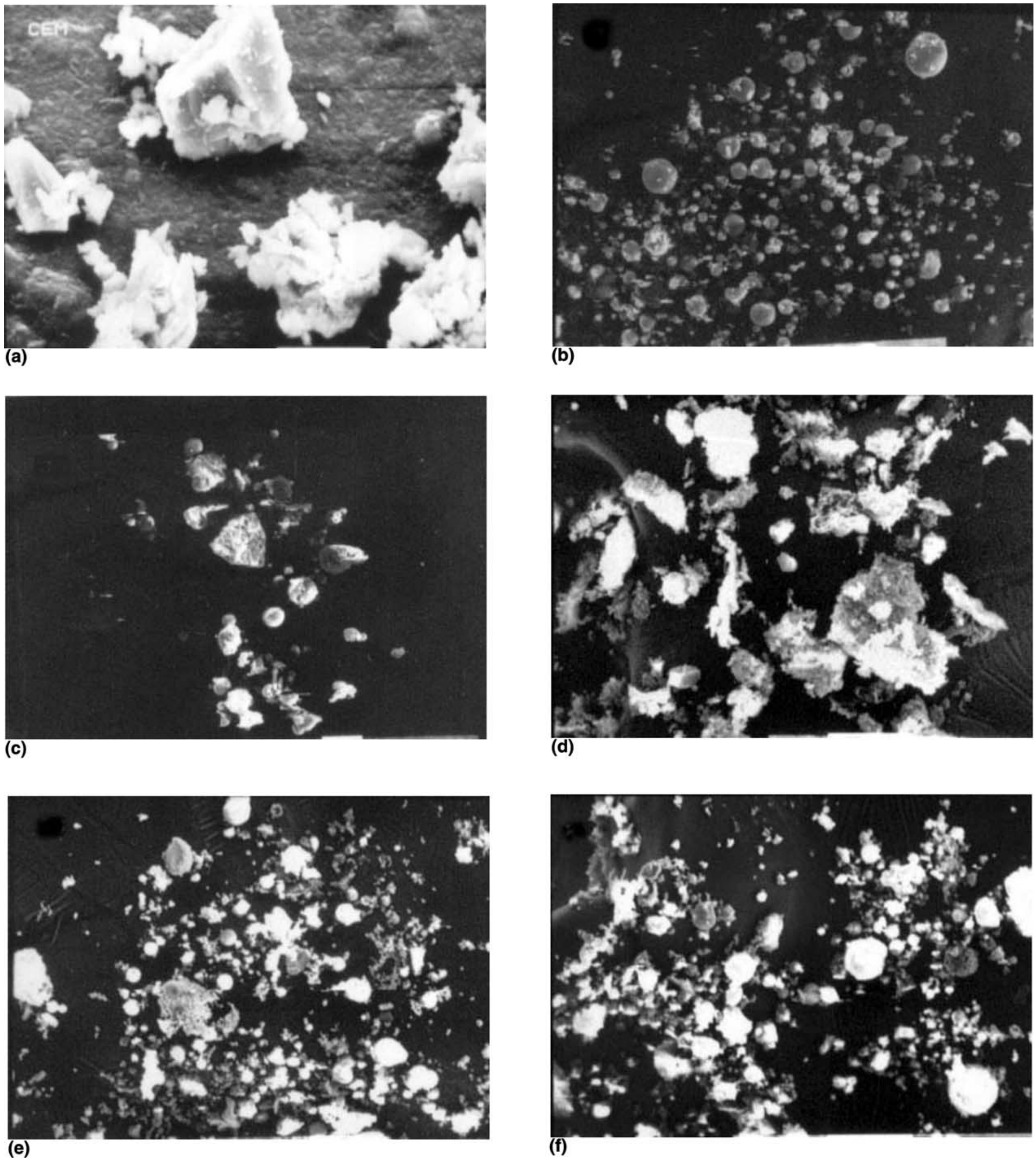

Fig. 3. Particle shapes of Portland cement type I and 5 sources of fly ashes by SEM. (a) Portland cement type I. (b) Fly ash-FM. (c)m Fly ash-FR. (d) Fly ash-FS. (e) Fly ash-FK. (f) Fly ash-FN.

compositions were different. In the case of mortar FK-S, it had the same particle size distribution as the mentioned fly ashes, but $W/(C+F)$ was higher ($W/(C+F) = 0.70$) so that the strength development rate was lower. In the same manner, mortars FN-M and FS-M had the same $W/(C+F)$ of 0.70, but the fineness was different, thus gave the difference of compressive strength. Mortars FM-M and FM-S ($W/(C+F) = 0.67$) also gave the same results (see Fig. 5). It can be concluded from the results that the strength development rate of fly ash–cement mortars depends on two major parameters, i.e. the fineness of fly ash and $W/(C+F)$.

3.6. Strength activity index

According to ASTM C 311, the strength activity index is defined as the ratio (in %) between the compressive strength of mortar containing substituting materials

Table 2
Chemical composition of Portland cement type I and original fly ashes

Sample type	Chemical composition (%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	LOI
Cement	20.62	5.22	3.10	64.99	0.91	0.07	0.50	2.70	1.13
FM	46.25	26.43	10.71	7.61	2.21	1.11	3.07	1.85	0.23
FR	45.02	36.21	4.09	3.64	0.54	0.44	0.31	0.48	5.32
FS	43.92	36.62	3.97	3.05	0.55	0.38	0.44	0.64	7.52
FK	47.39	22.73	6.29	8.36	2.64	0.63	2.95	3.38	3.12
FN	49.04	37.91	2.75	1.03	0.39	0.38	0.52	0.18	4.70

Table 3
Normal consistency of cement paste and pastes containing fly ashes as cementitious material

Type of paste	Normal consistency (%)	Initial setting time (min)	Final setting time (min)
Cement	24.7	107	175
FM-O	*23.4*	*119*	*210*
FM-L	25.1	117	195
FM-M	25.2	115	195
FM-S	24.4	105	190
FR-O	*28.4*	*124*	*195*
FR-L	26.2	122	190
FR-M	26.2	116	180
FR-S	26.2	107	175
FS-O	*29.3*	*135*	*220*
FS-L	27.1	130	220
FS-M	27.2	123	210
FS-S	27.2	121	200
FK-O	*34.8*	*154*	*240*
FK-L	26.3	141	225
FK-M	26.1	130	210
FK-S	26.4	122	210
FK-O	*28.8*	*133*	*190*
FN-L	26.7	111	180
FN-M	26.8	108	180
FN-S	26.5	105	175

20% by weight of binder and that of the control mortar at the same ages. The strength activity indices of all fly ash–cement mortars are calculated and shown in Table 5. Only mortar FR-O at 7 days had a strength activity index less than 75%, the rest were higher and conformed to ASTM C 618 which specifies that the strength activity index must be higher than 75% at the ages of 7 or 28 days. In all cases, as the fineness of fly ash increased so did the strength activity index. In the case of mortar FM-S, a strength activity index of 121% was achieved at the age of 90 days when the fly ash median particle size was reduced from 90 to 1.9 μm.

It has been claimed in the literature [8,15] that coarse fly ash is inert due to containing highly crystalline phases and having a relatively small specific surface area. In this experiment, the coarse fly ashes from different sources were ground to smaller sizes so that their phase should remain unchanged as reported by Paya' et al. [16]. The current results demonstrated that the fineness of ground coarse fly ash influence significantly the strength activity index.

Table 6 shows the comparison of strength activity indices at 7 and 28 days between classified fly ash–cement mortars obtained from [17–19] and those of ground coarse fly ash mortars from the present study. It is clear that there is no significant difference between the strength development rates of mortars containing the ground coarse and classified fly ashes when the median particle sizes of the fly ashes are similar. It indicates that more than 85% of the control mortar strength is achieved at 7 days and generally in excess of 100% at 28 days.

3.7. Influence of fineness of fly ash

Fraay et al. [20] investigated the pozzolanic reaction of fly ash and suggested that the reaction started after one week and before this period it behaved as an inert material. However, the tests were made without taking into account the fineness of the fly ash. A similar investigation was carried out on different finenesses of fly ash by Sybertz and Wiens [17], they found that the fineness of fly ash accelerated the pozzolanic reaction. Fig. 6 shows the relationship between median particle size of fly ash and strength activity index of mortars when fly ash replacement is 20% by weight of cementitious material. Obviously, mortars mixed with finer fly ash gained faster strength and higher strength activity index. The relationship applies for mortar of ages from 3 to 90 days.

Some more information can be interpreted from Fig. 6. For example, the mortars with super fine fly ash ($d_{50} = 3$ μm) can gain strength activity index more than 90% of the control within 3 days and 100% is possibly aimed at 10 days. While the fly ash with $d_{50} = 15$ μm, needs about 90 days to reach 100% of strength activity index, the use of fly ash with $d_{50} = 30$ μm seems never

Table 4
Water-cementitious material ratio, flow, water requirement of mortars, and compressive strength

Type of mortar	W/(C + F)	Flow	Water requirement (%)	Compressive strength (MPa)					
				3-day	7-day	14-day	28-day	60-day	90-day
Standard	0.68	106	100	18.0	23.5	27.3	31.8	34.1	35.8
FM-O	*0.67*	*111*	*99*	*13.5*	*18.9*	*23.4*	*27.7*	*30.9*	*32.4*
FM-L	0.68	107	99	14.5	19.6	26.6	31.5	34.2	36.4
FM-M	0.67	111	98	16.4	22.6	28.8	35.6	38.8	41.0
FM-S	0.67	107	98	16.7	22.7	31.6	37.9	41.0	43.5
FR-O	*0.71*	*113*	*104*	*12.3*	*16.4*	*20.5*	*24.2*	*28.2*	*30.8*
FR-L	0.70	114	103	13.5	18.1	22.6	26.6	31.3	33.9
FR-M	0.70	112	103	14.4	19.7	23.5	27.6	31.6	34.7
FR-S	0.68	106	100	15.2	20.1	25.9	31.7	34.9	37.0
FS-O	*0.69*	*105*	*101*	*14.1*	*18.8*	*23.3*	*28.6*	*32.6*	*35.0*
FS-L	0.72	110	105	13.6	18.6	22.0	28.2	31.3	33.7
FS-M	0.70	114	102	14.8	20.4	24.3	28.9	32.4	35.1
FS-S	0.68	106	100	16.2	23.2	27.7	33.3	36.1	38.0
FK-O	*0.73*	*109*	*106*	*14.0*	*19.5*	*22.2*	*26.2*	*27.7*	*28.3*
FK-L	0.71	108	103	15.1	21.4	25.1	29.5	31.6	32.7
FK-M	0.70	109	103	16.7	22.1	27.5	31.1	32.6	33.5
FK-S	0.70	105	102	17.0	22.1	27.7	31.5	33.4	34.0
FN-O	*0.71*	*105*	*103*	*14.0*	*18.9*	*23.9*	*28.7*	*31.9*	*34.8*
FN-L	0.72	108	105	14.3	19.1	24.1	28.9	32.4	35.9
FN-M	0.70	107	102	14.8	20.5	24.8	31.4	35.5	37.5
FN-S	0.68	108	100	16.1	22.3	26.7	33.1	36.5	38.5

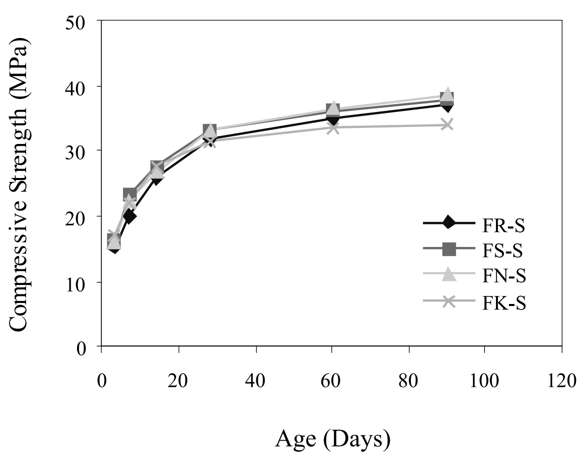

Fig. 4. Compressive strength of mortars with the same fineness of fly ash.

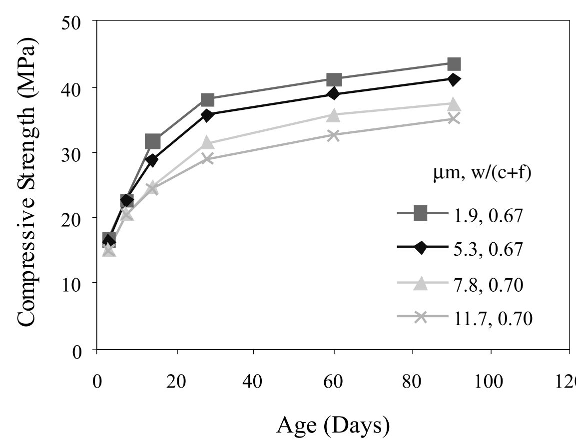

Fig. 5. Compressive strength of mortars with the same W/(C + F).

gaining this much percentage. It can be observed from the same figure that strength activity index is accelerated during day 7–day 14. Consider the slope of regression line of days 7 and 14, a big jump in strength gain can be seen when the d_{50} of fly ash is lesser than 10 µm. More than 10% increase of strength activity index can be detected when using fly ash with $d_{50} = 2$ µm while only about 2–3% of strength gain in the same period when the d_{50} of fly ash was bigger than 30 µm. This suggests that to enhance early strength of fly ash mortar or concrete, very fine fly ash must be involved.

4. Conclusions

An experimental study was conducted to investigate the influence of chemical and physical properties of ground coarse fly ashes from different sources on the compressive strength of mortar. The following conclusions can be drawn:

1. For Class F fly ash used in this study, the fineness, not the chemical compositions, has the significant effect on compressive strength of mortar. The mortars with finer fly ashes gained higher compressive strength than those with the coarser ones.

Table 5
Strength activity index of fly ash–cement mortars

Type of mortar	Median particle size (μm)	Strength activity index (%)					
		3-day	7-day	14-day	28-day	60-day	90-day
Standard	13.0	100	100	100	100	100	100
FM-O	*28.5*	*75*	*80*	*86*	*87*	*91*	*91*
FM-L	9.0	81	83	97	99	100	102
FM-M	5.3	91	96	105	112	114	115
FM-S	1.9	93	97	116	119	120	121
FR-O	*32.0*	*68*	*70*	*75*	*76*	*83*	*86*
FR-L	15.4	75	77	83	84	92	95
FR-M	10.5	80	84	86	87	93	97
FR-S	4.7	84	85	95	100	102	103
FS-O	*18.3*	*78*	*80*	*85*	*90*	*96*	*98*
FS-L	17.2	76	76	81	87	92	94
FS-M	11.7	82	87	89	91	95	98
FS-S	5.3	90	99	101	105	106	106
FK-O	*44.2*	*78*	*83*	*81*	*82*	*81*	*79*
FK-L	10.5	84	91	92	93	93	91
FK-M	4.8	93	94	101	98	96	94
FK-S	3.7	94	94	101	99	98	95
FN-O	*27.0*	*78*	*80*	*87*	*90*	*93*	*97*
FN-L	13.7	79	81	88	91	95	100
FN-M	7.8	82	87	91	99	104	105
FN-S	4.2	89	95	98	104	107	107

Table 6
Comparison of strength activity index of processed fly ash–cement mortars at 7 and 28 days

Age (days)	Strength activity index (%)							
	This study					From Ref. [17] ~6 μm	From Ref. [18] ~3 μm	From Ref. [19] ~3 μm
	FM-M ~5 μm	FR-S ~4 μm	FS-S ~5 μm	FK-S ~4 μm	FN-S ~4 μm			
7	96	85	99	94	95	N.A.	95	105
28	112	100	105	99	104	109	112	112

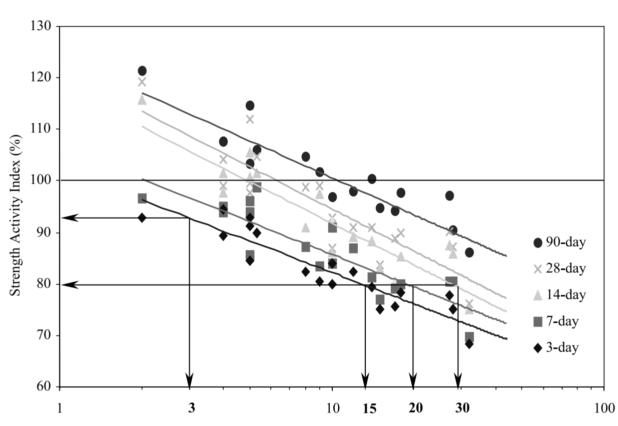

Fig. 6. Relationship between median particle size and strength activity index.

2. Finer fly ash had a significant effect on mortar strength as early as 3 days. Strength activity indices as high as 121% could be obtained at 90 days when coarse fly ash was ground to median particle size of 1.9 μm.
3. No significant difference in compressive strength was found between mortars containing classified and ground coarse fly ashes of similar median particle size.

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