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A Study of Strength Activity Index of Ground Coarse Fly Ash with Portland Cement

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ABSTRACT Fly ash, from Mae Moh power plant, was classified by air classifier to yield fine and coarse fractions. The coarse fly ash was ground and classified again into 3 sizes. Four different sizes of fly ash from the process including the original fly ash were replaced cement 20% by weight to make mortars. Chemical and physical properties of all fly ashes were tested. Setting times of fly ash-cement pastes and compressive strength of fly ash-cement mortars were investigated, and compared with those of the control. The results revealed that slight change in chemical composition of processed fly ashes did not give much effect on the compressive strength, whereas, the fineness of fly ash played a more important factor on the compressive strength development rate. More than 110% of strength activity index of ground coarse fly ash mortar can be achieved as early as 1 to 3 days since the coarse fly ash is not in crystalline phase.

KEYWORDS: fly ash, coarse fly ash, fineness, mortar, strength activity index.

INTRODUCTION

Fly ash, as defined by ACI 116,[1] is the finely divided residue resulting from the combustion of ground or powdered coal and which is transported from the firebox through the boiler by flue gases; known in UK as pulverized-fuel ash. In 1985, 11 fly ashes from different sources in the United State were tested. The results showed that calcium content and particle size distribution were the most important parameters governing the strength development rate.[2] Fly ash was improved its properties by classifying the particle size, reportedly the smaller size gave the higher strength and the faster strength development rate.[3,4] Furthermore, fly ash was reported that its replacement in concrete improved workability and reduced water demand[5]. It was proved that very fine fly ash was beneficial for concrete. In Thailand, Mae Moh power plant is the largest plant producing a by-product, fly ash, approximately 9000 tons a day or about 3 million tons per year[6] With this huge quantity, a lot of money has been wasted on transportation, disposal, and protection the pollution from fly ash with gaining nothing. The attempt of utilizing Mae Moh fly ash in concrete has been pursued for more than two decades, however, the use of fly ash is limited since its properties are diverse and no researchers pay serious attention on developing its properties.

Mae Moh fly ash was firstly improved its properties by ground to smaller size. The results showed that the small particle size of fly ash was a good source of pozzolanic material[7]. Later, classified fly ash by air cycling was developed at King Mongkut's Institute of Technology Thonburi (KMITT) in 1996 which be able to select the mean particle size down to 3 micron.[8] The test results of those fly ashes supported the former papers.[3,4] However, a question is raised on whether coarse fly ash can be used as pozzolanic material. Many researchers concluded that the coarse fly ash gave a very low compressive strength when used up to 30% of cement replacement.[3,4,7,8] Some pointed out that the large particle sizes carried the crystalline phase which was inactive to pozzolanic reaction and should be avoided to introduce in cement or concrete.[4]

It would be more beneficial in any case if both fine and coarse fly ashes can be utilized in concrete with less restriction. In this paper, the strength activity index of ground coarse fly ash was investigated and compared with those of classified fine fly ash. The results would indicate the feasibility of using ground coarse fly ash in cement manufacturing as well as in concrete. The objective of this research was to show the means of improving coarse Mae Moh fly ash in order to utilize it as a good cementitious material. Compressive strengths and other properties of ground coarse fly ash when mixed with Portland cement were mainly investigated to interpret the results.

Materials and Methods

Materials

Materials used in this experiment consisted of ordinary Portland cement, fine aggregate (river sand) and fly ash from Mae Moh power plant. The fly ash was classified to yield fine and coarse particle sizes. The coarse fly ash was ground to small and classified to have different particle sizes as described below:

Fly Ash

Figure 1 is the schematic for fly ash preparation. Figure 2 shows the air classifier and grinding machine used in this experiment. Original fly ash (O) was firstly classified by air classifier into fine (F) and coarse (C) fractions. The coarse fraction of fly ash (C) was ground into smaller particle size and then classified by air classifier again. The coarse outcome from air classifier was collected and denoted as CC (coarse and coarse). Again, the fine fraction (CF-coarse and fine) was classified into two parts denoted as CFC (coarse, fine, and coarse) and CFF (coarse, fine, and fine), respectively. Fly ashes O, F, CC, CFC, and CFF were used in this experiment.

Scanning Electron Microscope (SEM) of fly ashes and cement are shown in Figure 3. Original fly ash (O) and fly ash F showed their solid spherical shape like a ball, where as the others were rough and angular. All fly ashes were checked for their fineness by the sieve No. 325 (opening 45 micron) and the results were shown in Table 1. Mean particle size and specific gravity were also investigated and also shown in this Table. It was clear that the original fly ash (O) with mean particle size of 40.0 micron, was classified to the smaller size as fly ash F with mean particle size of 18.0 micron. After fly ash CC was ground and classified again, the average mean particle size was diminished from 50.0 micron to 19.5 and 5.0 micron, namely CFC and CFF, respectively. Figure 4 is the particle size distribution of all fly ashes and cement. All fly ashes were investigated for their influence on strength activity index after mixed with cement.

Table 1. Physical properties of cement and fly ash.

Type of Materials	Specific Gravity	Retained on Sieve No.325 (%)	Mean Particle Size (micron)
Cement(C)	3.15	24.0	16.0
Fly Ash (O)	1.95	46.2	40.0
Fly Ash (F)	2.51	12.6	18.0
Fly Ash (CC)	2.07	68.8	50.0
Fly Ash (CFC)	2.38	38.0	19.5
Fly Ash (CFF)	2.56	0.0	5.0

Chemical Composition

All fly ashes were chemically analyzed by X-ray Fluorescence Spectroscopy and the results were shown in Table 2. According to ASTM C 618, fly ash is categorized to 2 types as Class C and Class F. Class F fly ash must contain the main composition SiO_2+Al_2O_3+Fe_2O_3 more than 70%. While Class C should have those oxides not less than 50%. The original fly ash used in this experiment can be categorized as Class F since the sum of the main composition is 80.24%.

Chemical composition of those fly ashes after classified were slightly changed; however, it was interesting to note that the finer fly ash contained more SO_3 than the coarser one. With bigger particle size of fly ash, the Fe_2O_3 content appeared to increase. This implies that Fe_2O_3 outweigh than SO_3. The increase of SO_3 in the finer fraction should be

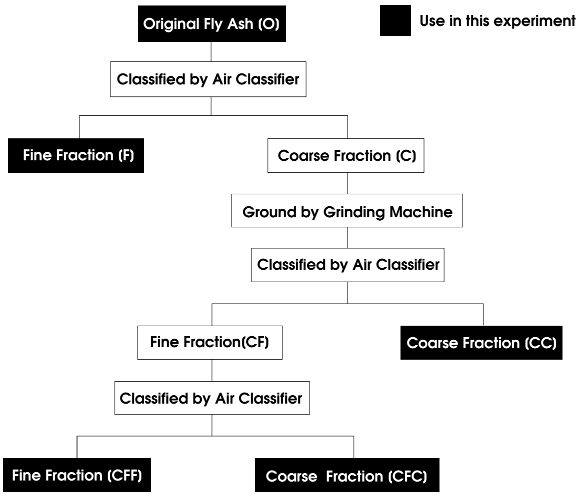
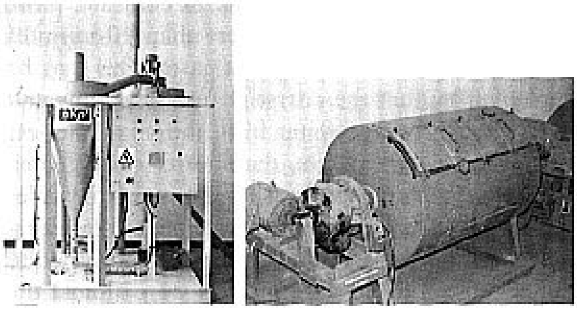


Fig 1. The schematic for fly ash preparation.

Table 2. Chemical composition of fly ashes and cement.

Chemical Composition (%)	Cement C	Fly Ash				
		O	F	CC	CFC	CFF
SiO_2	20.62	45.94	45.75	44.40	46.19	47.80
Al_2O_3	5.22	25.62	25.27	25.04	25.89	26.97
Fe_2O_3	3.10	8.68	8.80	10.01	9.03	6.66
CaO	64.99	9.39	9.32	11.12	9.38	7.90
MgO	0.91	2.36	2.29	2.63	2.49	2.18
Na_2O	0.07	1.43	1.53	1.31	1.33	1.33
K_2O	0.50	2.71	2.79	2.34	2.56	3.00
SO_3	2.70	1.23	1.82	0.46	0.49	0.99
Loss On Ignition (LOI)	1.13	1.22	1.12	0.86	0.87	2.20



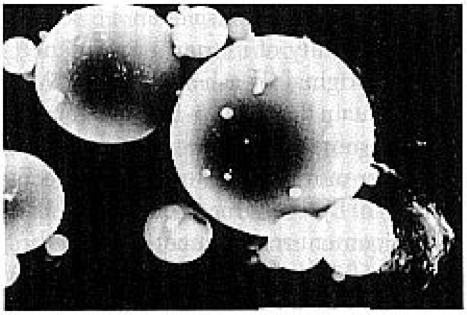
Air Classifier Machine **Grinding Machine**

Fig 2. Air classifier and grinding machine.

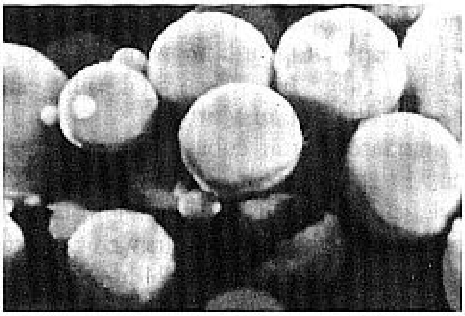
cautioned since ASTM C 618 limits it not more than 5%. Loss on ignition (LOI) also varied with the fineness, when the fineness increased, LOI increased as well. The former researches[7,8,9] gave the same results and mentioned that the increase of LOI was caused from the smaller particle size of fly ash which was easier to get burnt and it did not relate to the increase of carbon which was harmful to cementitious property. The sum of SiO_2+Al_2O_3+Fe_2O_3 of fly ashes before classifying or after grinding were almost the same. That is, it can be concluded that the process of air classifying and grinding do not have much effect on their chemical composition.

Normal Consistency and Setting Times

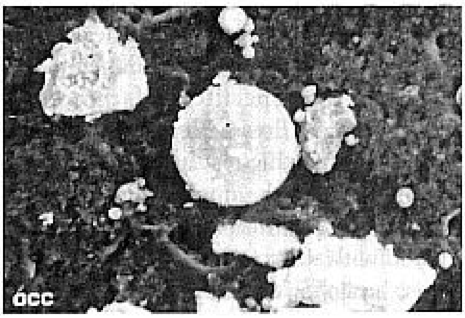
Normal consistency and setting times of cement



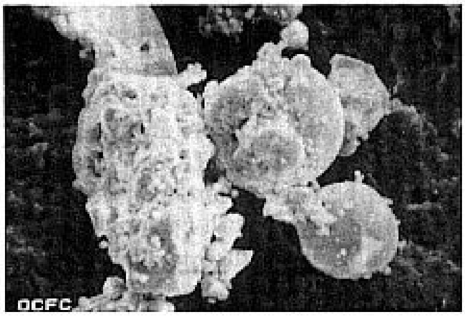
O



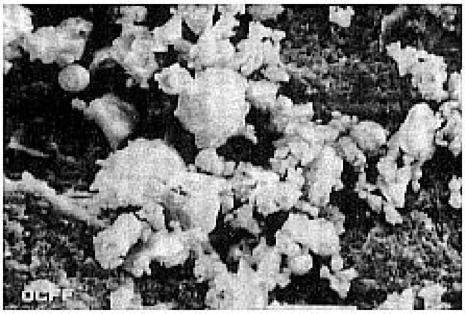
F



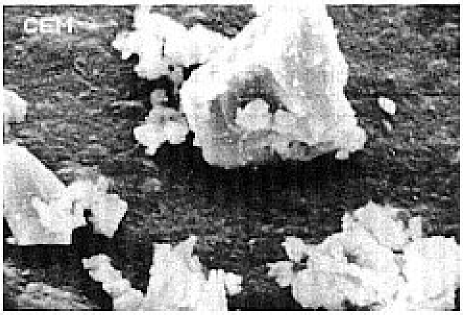
CC



CFC



CFF



CEMENT

Fig 3. SEM of fly ashes and cement.

and fly ash-cement pastes were tested in accordance with ASTM C 191. The fly ash-cement pastes were composed of 20% of each type of fly ash by weight, in replacing cement.

Detail of Mortar Mixes

Six mortar mix proportions were used in this investigation to study the influence of the fineness of ground coarse fly ash on strength activity index and they were shown in Table 3. Mix No. I was the control sample with the proportion cement to sand of 1:2.75 by weight and with the water to cement ratio of 0.64. No fly ash was used in mix I. Mix Nos. II, III, IV, V, and VI, the cement was replaced by fly ash 20% by weight. Water to cementitious material (cement + fly ash) ratio of mix Nos. II, III, IV, V, and VI were varied between 0.60 to 0.69, depending on the fineness of fly ash, to maintain flow of mortar between 110 ± 5% in accordance with ASTM C 230.

Compressive Strength of Mortar

The standard mortar cubes of 50x50x50 mm^3 were cast in brass molds and the mortars were removed from the molds after 24 hours. The compressive strength of the mortars were performed as prescribed by ASTM C 109 at 24 hours, 3, 7, 14, 28, 60, and 90 days of curing.

Results and Discussion

Normal Consistency and Setting Times

Many reports[5,7,8] showed that fineness, chemical composition, and mix proportion had enormous influence on the setting times of fly ash-cement paste. Table 4 shows the normal consistency and setting times of cement and fly ash-cement pastes. The investigation showed that there was not a significant relationship between setting time and fineness of fly ash; however, setting time tended to decrease while coarse fly ash was used. After fly ash was classified to smaller size (fly ash F), the setting time became as long as those of the control. In contrary, paste mixed with fly ash CC set more than 40 minutes shorter than that of the cement paste. This may be explained by that the coarse fly ash is porous and quickly absorbs free water from the mix. The less free water in the matrix, the shorter setting time would be. While coarse fly ash was ground to smaller size (fly ash CFF), the cavities were broken resulting in less porous so that no free water was absorbed to the cavities and the setting times were almost the same as those of cement paste. However, as prescribed by ASTM C 150, initial setting time should be longer than 45 minutes so that all types of fly ash-cement pastes are in the allowance.

Workability

As shown in Table 3, it was seen that by 20% replacement, original fly ash did not essentially affect on the workability of mortar. For instance, mortar II with the original fly ash still needed W/(C+F) of 0.64 to maintain flow of 105-115% as compared with the control mortar.

Consider mortar mix No. III which contained a proportion of fly ash F (mean diameter = 18 micron), the water content requirement to meet the percent flow was 0.60. That was lower than the control and the lowest while mortar mix No. VI containing fly ash CFF (mean diameter = 5 micron), the smallest, needed water to cementitious material ratio of 0.63 to meet 105-115 percent flow. In the recent paper[10], it was found that percent flow depended on mean particle size and specific surface area. Coarser fractions gave less flow table spread values than the finer ones so that this result dispute to the former; however, those fly ash samples were diminished only by air classifier. Thus, its shape was still sphere compared with the rough surface of CFF in present paper as shown in Figure 3. The phenomenon could be explained by that the lubricating effect of small solid spherical shape was probably canceled by water absorption on the increased rough surface area. The

Table 3. Mix proportion of mortar.

Mix No.	Cement (%)	Fly Ash (%)	Type of Fly Ash	Flow (%)	W/(C+F)
I	100	-	-	111	0.64
II	80	20	O	115	0.64
III	80	20	F	114	0.60
IV	80	20	CC	114	0.69
V	80	20	CFC	115	0.66
VI	80	20	CFF	110	0.63

Table 4. Normal consistency and setting times of fly ash-cement pastes.

Mix No.	Type of Fly Ash	Normal Consistency (%)	Initial Setting Time (minute)	Final Setting Time (minute)
I	-	24.5	115	140
II	O	23.8	90	125
III	F	25.3	100	145
IV	CC	23.5	70	100
V	CFC	24.8	115	150
VI	CFF	24.0	95	130

other reason that may support the idea is the difference of water requirement between CFF mortar (mortar mix No. VI) and CFC mortar (mortar mix No. V) is slightly changed even though the mean particle size of CFF is smaller than that of CFC almost 4 times. This can make a point that the mean particle size of fly ash do not dominate the workability of fly ash mortar but shape of fly ash has much effect on the workability.

Strength Activity Index

As prescribed by ASTM C 311, strength activity index is defined as

Strength Activity Index (SAI) = (A/B) x 100

where A = average compressive strength of fly ash-cement mortar cube

B = average compressive strength of control mortar cube

Table 5 shows the compressive strengths and the strength activity indices of fly ash cement mortars at the given ages. The data clearly showed that very fine fly ash increased the compressive strength even in early ages. In contrast, coarse fly ash affected on slow strength development. Mortar mix No III, for instance, containing the fine fly ash F gave compressive strength higher than those of the controls at all ages. This may be caused from both less water to cementitious material ratio and pozzolanic activity of fly ash. Mortar mix No VI, containing fly ash CFF, which was diminished by grinding after had been classified to be finer fraction, also gave the high strength with almost the same amount of water as of the control. Again, this showed that the lubricating effect of spherical solid shape of ground classified fly ash was canceled and the packing effect of small particle size and pozzolanic reaction were fully involved.

It should be observed that strength activity indices of mortar mix Nos. III and VI which contained fly ash F and CFF, respectively were almost the same between the ages of 28 days to 90 days. However, at early ages, mortar mix No VI gave higher strength activity index than mortar mix No III. This is due to fly ash CFF has smaller particle size than that of fly ash F, so that pozzolanic activity can be reacted faster. The result conforms to Mehta's report.[2] From Figure 5, it can be seen that very fine fly ashes boost compressive strength of mortar even in early ages as in mix Nos. III, V, and VI. Mortar mix Nos V and VI both contained ground coarse fly ash resulting in high strength activity index and they could achieve the strength as high and early as the classified one. Thus, grinding can improve pozzolanic activity of coarse fly ash and proves that the coarse fly ash is not in crystalline phase. The results did not agree with Berry *et al.*[4] which reported that coarse fly ash should not be used in concrete because it contained high portion of crystalline phase. The low strength of coarse fly ash mortar from the work of Berry et al. was due to the less surface area to react with lime release from cement.

It is interesting that mortar mix Nos III, V, and VI containing fine fly ash gave higher strength activity indices in early age than those in middle age and then heading up to peak again at 90 days. It is well known that slope of compressive strength development of Portland cement type I is precipitous before 28 days and becomes flat hereafter, whereas, pozzolanic reaction keeps longer and may extend over 3 years.[11] Therefore, it is clear that after 28 days, the index of fly ash-cement mortar should get higher with time. In early age, with less water to cementitious material ratio (mortar mix No III), with packing effect and pozzolanic reaction from tiny particle size (mortar mix Nos III, V, VI), the surplus early strength index could be obtained.

Considering Figure 6, the trends show that smaller particle size of fly ash generates higher compressive strength than the coarser one. Mix No VI, for example, achieved the strength activity index

Table 5. Compressive strength of mortar (MPa) and strength activity index (%).

Sample	Type of Fly Ash	Compressive Strength (MPa) – **Strength Activity Index (%)**						
		1-day	3-day	7-day	14-day	28-day	60-day	90-day
I	-	11.4-**100**	15.8-**10 0**	21.9-**100**	27.0-**100**	30.2-**100**	32.1-**100**	32.8-**100**
II	O	5.9-**52**	12.2-**77**	17.9-**82**	22.1-**82**	25.8-**85**	30.2-**94**	31.1-**95**
III	F	12.6-**111**	15.8-**100**	23.4-**107**	30.6-**113**	35.4-**117**	39.6-**123**	42.5-**130**
IV	CC	5.9-**52**	10.8-**68**	21.2-**97**	26.5-**98**	31.0-**103**	33.3-**104**	34.6-**105**
V	CFC	12.1-**106**	17.3-**110**	25.9-**118**	29.2-**108**	32.9-**109**	35.6-**111**	36.3-**111**
VI	CFF	12.8-**113**	19.8-**125**	27.3-**125**	30.1-**114**	35.5-**118**	39.1-**122**	41.0-**125**

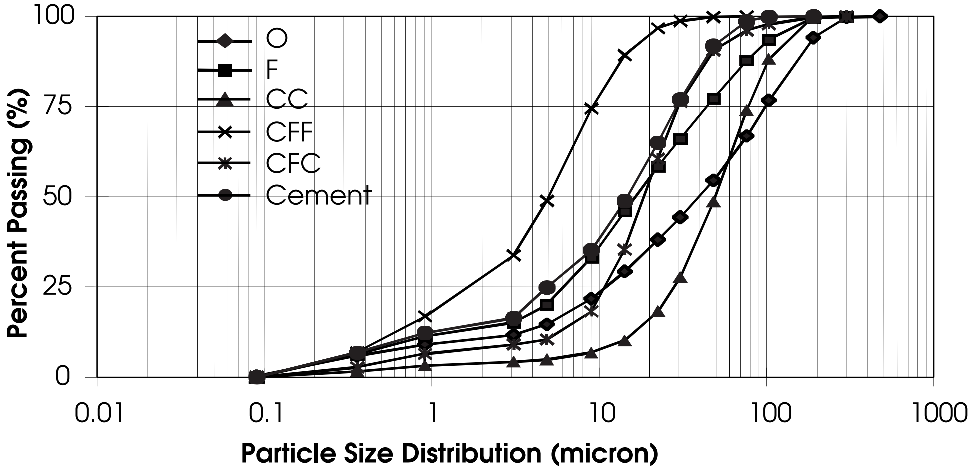


Fig 4. Particle size distribution of fly ashes and cement.

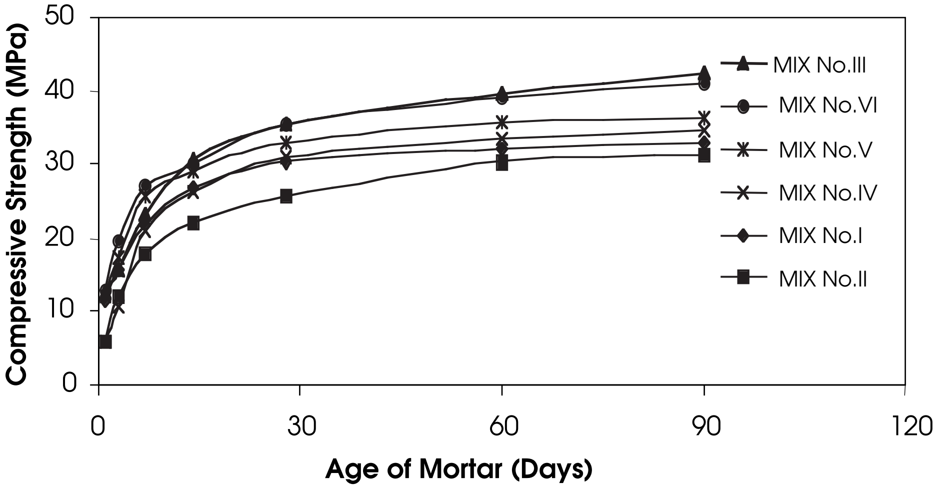


Fig 5. Relationship between compressive strength and age of mortar.

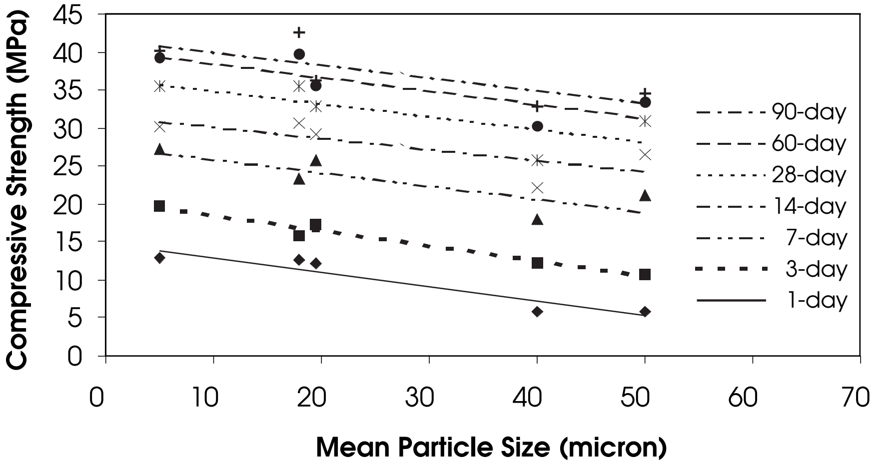


Fig 6. Relationship between compressive strength and mean particle size of fly ash.

of 113%, 125%, and 125% at 1, 3, and 7 days, respectively. This conforms to the recent work of Angsuwattana *et al*.[9] They reported that the use of classified fly ash with the mean particle size of 2.8 micron replacing cement 35% by weight showed that over 100% of strength activity index could be achieved as early as 7 days. However, it is noted that the shape of fly ash also affects on compressive strength. The ground coarse fly ash CFC (mean diameter of 19.5 micron) had almost the same particle size as of the classified fly ash, F, but the compressive strength of mortar No. V was by far lower than that of mortar mix No. III (with fly ash F). Fly ash F (see Figure 3) was in spherical shape, so that, it needed less water to maintain the specified workability. With lower water to cementitious material ratio, compressive strength was automatically increased. Figure 6 can also be interpreted that linear relation between compressive strength and mean particle size of fly ash can be constructed at all ages when 20% of fly ash is replaced in cement to make mortar.

Conclusions

In this experiment, the conclusions can be drawn as follows:

1. Up to 110% of strength activity index can be achieved when coarse fly ash is ground to smaller size.
2. Strength activity index of coarse fly ash can be improved by grinding and coarse fly ash is not in crystalline phase.
3. For a good quality of fly ash, by classifying or grinding, the important factor is its fineness. Fly ash with small particle size increases ultimate strength as well as rate of strength gain of fly ash-cement mortar.
4. With classifying or grinding processes, setting times of all fly ash-cement pastes are acceptable since they are longer than 45 minutes as specified by ASTM C 150.
5. When keeping the same workability of mortar, the use of smaller size of fly ash demands less water than the use of coarser one.

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