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Influence of fly ash fineness on strength, drying shrinkage and sulfate resistance of blended cement mortar

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Abstract

In this paper, the influence of fineness of fly ash on water demand and some of the properties of hardened mortar are examined. In addition to the original fly ash (OFA), five different fineness values of fly ash were obtained by sieving and by using an air separator. Two sieves, Nos. 200 and 325, were used to obtain two lots of graded fine fly ash. For the classification using air separator, the OFA was separated into fine, medium and coarse portions. The fly ash dosage of 40% by weight of binder was used throughout the experiment. From the tests, it was found that the compressive strength of mortar depended on the fineness of fly ash. The strength of mortar containing fine fly ash was better than that of OFA mortar at all ages with the very fine fly ash giving the highest strength. The use of all fly ashes resulted in significant improvement in drying shrinkage with the coarse fly ash showing the least improvement owing primarily to the high water to binder ratio (W/B) of the mix. Significant improvement of resistance to sulfate expansion was obtained for all fineness values except for the coarse fly ash where greater expansion was observed. The resistance to sulfuric acid attack was also improved with the incorporation of all fly ashes. In this case the coarse fly ash gave the best performance with the lowest rate of the weight loss owing probably to the better bonding of the coarse fly ash particles to the cement matrix and less hydration products. It is suggested that the fine fly ash is more reactive and its use resulted in a denser cement matrix and better mechanical properties of mortar.

Keywords: Fineness; Fly ash; Compressive strength; Shrinkage; Sulfate attack

1. Introduction

It is known that not only the strength of concrete, but also its durability, is important to increase the service life of the structure. The use of certain pozzolans such as some fly ashes increases the durability through the pore refinement and the reduction in the calcium hydroxide of the cement paste matrix. One of the most important aspects of durability of concrete is the resistance to sulfate attack. Both sulfate solution and sulfuric acid solution are harmful to concrete. The other property which also influences the performance of structural concrete is the shrinkage especially the drying shrinkage which could induce cracking and thus reduces the ability of concrete to resist chemical attack. The effect of fly ash fineness on the strength, drying shrinkage and the resistance to sulfate solution attack is therefore of considerable interest.

It is generally agreed that the use of fine fly ash improves the properties of concrete. Erdogdu and Tucker [1] found that sieved fine fly ash increases the strength of mortar as compared to that of the mortar made from the original coarser fly ash. Lee et al. [2] tested fly ash with three fineness values and reported that the reacted calcium hydroxide of the fine fly ash cement paste was greater than that of the coarser fly ash cement paste indicating a larger degree of pozzolanic reaction of the fine fly ash. The glass content of the fly ash also contributes to the development of the strength. Chindaprasirt et al. [3] found that the glass content of the fine fly ash portion is higher than that of the coarser fly ash portion from the same batch, and that the use of fine fly ash reduces the water requirement of the mortar mix. The fine fly ash particles underwent a complete burning and are more spherical in shape and smoother surface as compared to the coarser fly ash particles. This reduction in water requirement together with the higher reactivity of the fine fly ash contributes to a higher strength of mortar as compared to a coarser fly ash.

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Drying shrinkage of fly ash blended cement concretes of similar strength grade varies quite widely with the source of fly ash. There is however little difference in drying shrinkage between 25% fly ash concrete and Portland cement concrete of similar normal strength concrete. Slightly better shrinkage for the fly ash concrete of higher grades was reported [4]. For mortar with the same flow, the drying shrinkage at early age was found to decrease with an incorporation of fly ash [3]. The early shrinkage of the mortar with finer fly ash was a little larger than that of the coarser fly ash mortar.

The resistance of concrete to chemical attack depends on the pore structure characteristics, the ability to neutralize the chemical solution and the passivation by the deposition of the reacted products [5]. The pore structure determines the permeability of concrete and thus the ingress of the chemical solution. The fine pore structure of fly ash concrete contributes to a larger resistance to the chemical attack [6]. It has been shown that the fine fly ash decreases the pore volume of the fly ash cement paste as compared to the coarser fly ash [7].

2. Materials

Cement: Ordinary Portland cement type I (OPC) similar to ASTM C150, Type I.

Aggregate: River sand with specific gravity of 2.65.

Fly ash: The fly ash was obtained from Mae Moh Power station in the north of Thailand and was classified into two groups.

Group 1. Graded fly ash. This group of fly ash was classified using the method of sieving and consists of three lots.

1. OFA: original fly ash complying to ASTM C618, Class F.
2. F200: fly ash passed sieve No. 200.
3. F320: fly ash passed sieve No. 325.

Group 2. Single size portion fly ash. This group of fly ash was classified using a cyclone separator and also consists of three lots.

1. FF: 10% fine portion fly ash obtained from air separator.
2. FM: 25% medium portion fly ash obtained from air separator.
3. FC: 65% coarse portion fly ash obtained from air separator.

The OFA, F200 and F325 are graded fly ash whereas the FF, FM and FM are different portions of the same batch as schematically shown in Fig. 1. The diagram shows some indications of the relative weight and size of different fly ashes. However, the real size limits are not truly indicated here since the coarser and finer portions of the fly ash always presented in the portions obtained from sieving and the air separation.

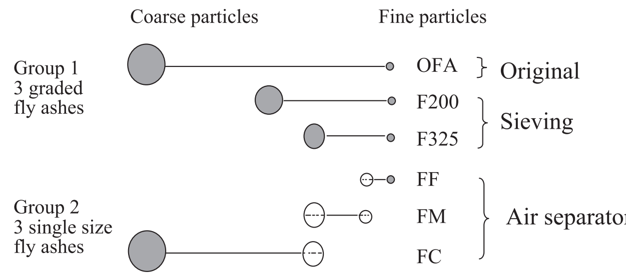

Fig. 1. Schematic diagram of two groups of six lots of fly ash.

3. Experimental procedures

3.1. Mix details

The fly ash replacement level of 40% by weight of the cementitious material was used for all the mortar mixes. This high level of replacement was selected such that the effect of the fly ash replacement could be detected.

3.2. Testing details

The strength test was done at the age of 3, 7, 28 and 90 days in accordance with the ASTM C109 using 50×5×50-mm cube specimen with sand to binder ratio of 2.75 and flow of mortar of 110±5%.

The drying shrinkage test was done in accordance with the ASTM C596 using 2×2×285-mm mortar bar with sand to binder ratio of 2.0 and flow of mortar of 110±5%. The shrinkage test was performed in the 50% R.H. chamber at 23±2 °C and four specimens were used for each mix.

The sulfate expansion test was done in accordance with the ASTM C1012 using sodium sulfate solution, 2×2×285-mm mortar bar with sand to binder ratio of 2.75. Six bars were used for each mix.

The sulfuric acid immersion test was done in accordance with the ASTM C267 using the 5% sulfuric acid solution, 2×25 mm cylindrical specimen with sand to binder ratio of 2.75 and flow of mortar of 110±5%. The specimens were cured until the age of 28 days. The specimens were then immersed in the 5% sulfuric acid at 23±2 °C. The weight loss of the specimens was monitored at 1, 3, 7, 28, 56 and 84 days after immersion. The reported loss was the average of three samples.

4. Results and discussions

4.1. Characteristic of fly ash

The physical properties of Portland cement and fly ashes are summarized in Table 1. The fineness of the original fly

Table 1
Physical properties of fly ash and Portland cement

Materials	Symbol	Specific gravity	Blaine fineness (cm^2/g)	% by weight of the OFA
Ordinary Portland cement	OPC	3.12	3500	NA
Original fly ash	OFA	1.99	3000	100
Fly ash passed sieve no. 200	F200	2.22	3900	50
Fly ash passed sieve no. 325	F325	2.36	4800	35
Fly ash—fine	FF	2.44	9300	10
Fly ash—medium	FM	2.11	4900	25
Fly ash—coarse	FC	1.88	1800	65

ash (OFA) was 3000 cm^2/g, which is about the same order as that of Portland cement. The specific gravity (SG) of the OFA was 1.99. As the fineness of the fly ash increased, the SG was also increased. The Blaine fineness of FF fly ash was 9300 cm^2/g indicating very fine portion of fly ash and the SG was 2.44 which was significantly higher than that of OFA. The fineness of FC fly ash was 1800 cm^2/g indicating a reasonable coarse portion and the SG was 1.88 which was lower than that of OFA. The significant difference in the specific gravity of fly ash of different fineness values was due mainly to the incomplete burning of the larger particles and hence the difference in the physical and chemical properties.

The chemical constituents of OPC and some of the fly ashes are given in Table 2. The OFA was light brown in color and the coarse fly ash is a lot darker whereas the fine fly ash is much lighter in color. With regard to the chemical constituents, the coarse fly ash contained a slightly higher SiO_2 and a slightly lower SO_3 and loss on ignition (LOI) in comparison to that of OFA. The total amount of Fe_2O_3 and alkali oxides which has the effect on the melting temperature of the ash was increased with an increase in the fly ash fineness. Similar physical and chemical properties of fly ash with different fineness values were reported by Lee et al. [2] and Erdogdu and Tucker [1].

4.2. Water requirements

The results of the water requirement for a constant flow of 110±5% for mortar are shown in Table 3. It can be seen that the incorporation of all fly ashes reduced water to binder ratio (W/B) as compared with the mortar made from OPC, except the mortar containing coarse fly ash (FC) which showed a significant higher W/B. In fact, while doing the flow test, slight segregation was observed for the FC fly ash mortar. The reduction in water requirement was due to the spherical shape and the smooth surface of the fly ash which helped the flow and workability of the mix. The water requirement of mortar made from F200 fly ash was the least. As the fineness of fly ash was further increased, the water demand was slightly increased due to the increase in the surface area and water requirement of the fine particles therefore the water requirement of the F325 fly ash mortar was slightly greater than that of the F200 mortar. For the very fine FF fly ash, the water demand of the mortar was lower than those of FM and FC mortar and was slightly larger than the mortar made from the fine F325 fly ash. For the medium FM fly ash, which lacked both the fine and the coarse fly ash portions, the water requirement was similar to that made from OFA. The higher water requirement of the coarse FC fly ash mortar was due to the irregular shape of larger particles of fly ash with rougher surface and in some cases with cenosphere. It should be pointed out here that this FC fly ash lacked both the fine and the medium portions fly ash which helped the workability of the mix and filling of the voids.

Table 2
Chemical constituents of OPC and fly ash

Type	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	LOI
OPC	20.8	5.2	3.8	64.3	1.2	0.1	0.4	2.0	1.3
OFA	40.1	21.0	11.8	12.7	2.41	1.43	2.83	2.25	2.28
FF	39.0	20.8	11.6	13.6	2.25	1.27	2.77	3.65	3.40
FC	44.2	20.9	12.0	12.6	2.41	1.21	1.21	1.40	0.75

Table 3
The W/B and the compressive strength of mortar at constant flow of 110%

Mix	W/B	Compressive Strength (MPa)			
		3 days	7 days	28 days	90 days
OPC	0.500	20.0	31.5	48.5	52.0
OFA	0.458	11.5	20.5	30.5	41.5
F200	0.402	15.5	19.0	38.5	53.5
F325	0.430	20.0	25.5	42.0	56.0
FF	0.439	25.0	31.0	53.5	61.5
FM	0.453	16.5	22.0	37.0	52.0
FC	0.572	8.5	13.5	23.0	29.0

4.3. Strength

The results of the strength of mortar are given in Table 3. It can be seen that significant improvement on strength development of mortars made from the fine F200, F325 and FF fly ashes, and the medium FM fly ash over that of OFA was evident.

For the graded fly ash, the incorporation of OFA reduced the strength of mortar especially at the early age of 3 and 7 days. The W/B was reduced to 0.458 which was quite substantial compared to the value of 0.500 for the OPC mortar. For the fine F200 mortar with the lowest W/B of 0.402, the strength was significantly improved as compared to that of the OFA mortar. In fact the strength at the age of 90 days was 53.5 MPa which was higher than 52.0 MPa of the OPC mortar at this age. For the F325 mortar which the W/B was slightly increased to 0.430, the strength of mortar was further improved over that of the F200 mortar at all ages. This indicated that the fine fly ash was very reactive and had a larger influence on strength

Table 4
Drying shrinkage of mortar bar tested to ASTM C 596

Mix	Drying shrinkage, 10^{-6} mm/mm						
	1 day	4 days	7 days	18 days	25 days	60 days	90 days
OPC	182	345	588	732	816	909	987
OFA	90	270	484	605	669	704	721
F200	103	333	566	633	702	729	768
F325	133	338	554	653	689	730	756
FF	86	291	537	628	665	688	709
FM	95	296	493	573	643	670	696
FC	141	342	567	693	773	802	852

than the reduction in the water demand. The use of the fine fly ash would also have a packing effect and the filling of the small voids and this would help with the strength development as well.

For the single size portion fly ash, the incorporation of the finest portion FF fly ash resulted in a very good strength development as compared to the OPC mortar. In fact, the strength of FF mortar was the highest at the age of 3, 28 and 90 days and the strength at the age of 7 days was also very high and was equal to that of the OPC mortar. The W/B of this mix was 0.439, which was a reasonable reduction in the water requirement. It should be pointed out here that the FF fly ash was very fine and thus very reactive. It is the higher reactivity of the FF fly ash that was responsible for the very high strength of mortar at all ages.

For the medium portion FM fly ash, the strength of the mortar was quite good. In fact the strength was similar to that of the F200 mortar despite the fact that the W/B of the FM mix was 0.453 and higher than that of the F200 mix. Although the FM fly ash lacked the very fine portion, it was still fine with the fineness value up to 4900 cm^2/g. This reasonably fine FM fly ash was therefore quite reactive and was responsible for a reasonable strength development of mortar.

For the coarse FC fly ash, the strength of the mortar was significantly lower than the others. The water requirement of the FC fly ash mix was drastically increased to 0.572. This together with the larger particle sizes and the lack of the fine portion were the main reasons for the low strength of this mortar. The FC fly ash lacked the fine portion of fly ash and it was this finest portion that contributed to the higher rate of the strength development [1].

4.4. Drying shrinkage

The results of drying shrinkage of the mortar bars are shown in Table 4. The incorporation of all fly ashes reduced the drying shrinkage in comparison with that of OPC. The use of OFA significantly reduced the drying shrinkage of mortar. Fine fly ashes, viz. F200, F325, FM and FF also significantly reduced the drying shrinkage of mortar. There was no definite trend on the effect of the fly ash fineness level on the drying shrinkage except that the OFA and all the fine fly ash reduced the drying shrinkage which was mainly related to the reduced water content and hence the lower W/B of the mixes. The coarse FC fly ash reduced the drying shrinkage of mortar, but to a lesser extent. It should be noted here that the use of FC increased the water requirement significantly and this should contribute to an increase in drying shrinkage. Also, the strength of the FC mortar was significantly lower than the other mortars and this would also contribute to a larger shrinkage.

4.5. Resistance to sulfate attack

The results of the expansion test of the mortar bars subjected to Na_2SO_4 solution are shown in Table 5. It is evident that the incorporation of all fly ashes except the coarse FC fly ash reduced the expansion of the mortar bars. For the graded fly ashes i.e., OFA, F200 and F325, the use of OFA reduced the expansion of the mortar bar after 105 days immersion to 233×10^{-6} mm/mm as compared to 344×1010^{-6} mm/mm of that of OPC mortar at the same age. The incorporation of finer graded F200 fly ash further reduced the expansion to 168×1010^{-6} mm/mm at the same age. It should be pointed out here that the water requirement of F200 mortar was the lowest and hence a dense mortar with less porosity was expected for this mortar. This would increase the resistance to the ingress of the sulfate solution. The incorporation of the F325 fly ash also produced mortar with relatively low expansion but higher than that of the F200 mortar. There is an indication here that the resistance of the mortar to the sulfate solution was related to the water content of the mortars. The expansion was decreased as the water content or the W/B was decreased. In addition, the fine fly ash was more reactive and hence reacted with calcium hydroxide more readily resulting in less calcium hydroxide and hence less susceptible for sulfate attack.

For the single size fly ash, the incorporation of the FF fly ash produced mortar with a low expansion. This was thought to relate to the low water content of the FF mortar and to a dense cement matrix. The use of fine fly ash also produced a denser and stronger mortar and resulted in a higher ability to resist the sulfate attack. For the medium FM fly ash, the expansion of the mortar bar was still low and comparable to that of OFA mortar. This increase in the

Table 5
Expansion of mortar bar in sulfate solution tested to ASTM C 1012

Mix	Expansion, 10^{-6} mm/mm						
	7 days	14 days	21 days	28 days	56 days	91 days	105 days
OPC	107	132	149	160	236	293	344
OFA	33	55	82	105	174	198	233
F200	21	42	65	87	137	172	168
F325	66	84	99	120	193	195	205
FF	78	94	96	106	128	141	180
FM	81	99	117	132	206	231	231
FC	55	111	171	249	482	562	611

expansion in comparison to the FF mortar was a result of an increase in the water content and a less dense matrix. For the coarse FC fly ash, the expansion was nearly twice the expansion of the OPC mortar. This coarse fly ash was less reactive and required a larger amount of water and hence produced a more porous mortar with a larger degree of susceptibility to the sulfate solution attack.

4.6. Resistance to sulfuric acid solution

The results of the weight loss of the mortar specimens subjected to 5% sulfuric acid solution are given Table 6. The rate of weight loss of all mortars except OPC and FC mortars increased after 3 days of immersion. For OPC mortar, the increase in weight loss was after 1 day of immersion. For FC mortar, after a small initial weight loss, a substantial weight gain was observed up to 56 days of immersion before the weight loss was detected at 84 days. The OPC mortar showed poor resistance to the 5% sulfuric acid solution. The incorporation of all fly ashes significantly reduced the rate of the early weight loss of the samples. The reduction in the rate of the weight loss was dependent on the fineness of fly ash. Roy et al. [8] also found that the OPC mortar showed poor resistance to 5% sulfuric acid solution and the use of fly ash increased the resistance.

For the graded OFA and F200 fly ashes, the weight loss of the OFA mortar after 28 days immersion was significantly lower than that of the F200 mortar. The surface of the coarse fly ash particles were not smooth and therefore provide good bonding with the cement matrix and would result in a smaller weight loss from the surface of the mortar due to the sulfuric acid attack. The sulfuric acid attacked mainly the hydration products. In this case, the F200 mortar containing finer fly ash would have been more advanced in the hydration at the time of immersion of the specimens into the sulfuric acid. Also, the volume of the OPC in the fine fly ash cement paste was larger than that of the coarser fly ash paste since the SG of the fine fly ash was considerably higher than that of the coarse fly ash. The higher amount of hydration product of the F200 mortar as compared to that of the OFA mortar would be susceptible for an attack by the sulfuric acid.

For the single size fly ash, it was clear that resistance to the sulfuric acid increased as the fineness of fly ash was decreased. The FC mortar showed no weight loss after 28 days immersion. The weight loss after 28 days immersion of the FM mortar was higher than the FC mortar and the FF mortar showed the highest weight loss in this series. It is known that the sulfuric acid attacks the calcium hydroxide and hydrates of calcium aluminate (CAH) as well as calcium silicate (CSH) [9]. The high resistance of mortar made with FC was due to the better bonding of the coarse fly ash particles with rougher surface with the cement matrix. In addition, the SG of the FF fly ash was 2.44, which was much higher than the value of 1.88 of the coarser fly ash. The lower calcium hydroxide and less hydration products as compared to that of OPC would help reduce the weight loss.

Table 6
Weight loss of mortar specimen subjected to 5% sulfuric acid

Mix	Weight loss, %					
	1 day	3 days	7 days	28 days	56 days	84 days
OPC	0	18	29	58	66	80
OFA	2	0	9	19	57	82
F200	1	1	14	41	66	78
FF	1	0	6	30	68	91
FM	1	0	4	18	41	86
FC	1	0	−1	−5	−4	17

5. Conclusions

The different fineness portions of fly ash appear to have a slight but consistent variation in physical and chemical properties consistent with other findings [1,2]. Test results also indicated that the fly ash with different fineness had a marked effect on the compressive strength as well as drying shrinkage and sulfate resistance. The incorporation of the fine fly ash reduced the water requirement of the mortar mixes. The coarse fly ash portion, lacking both the medium and the fine portions, on the contrary increased the water demand owing to the rougher surface of the coarser particles. The fine fly ash with high surface area was more reactive and thus resulted in the increase in strength. The fine fly ash also required less water owing to its spherical shape and smooth surface. Its packing or filling of the voids helped increase the compressive strength of the mortar.

For the drying shrinkage, all of the fly ashes reduced the shrinkage of the mortars. It is known that the drying shrinkage is influenced by many factors. The results indicated that the water content or the W/B was the prime factor as the fine fly ash mortars with low W/B exhibited low drying shrinkage and the coarse FC mortar with high W/B showed relatively high drying shrinkage.

With regard to the sulfate attack, it is evident that the incorporation of the fine fly ash reduced the expansion of the mortar bars immersed in the sodium sulfate solution. The fine fly ash reduced the W/B of the mortar and thus made it denser as well as stronger. The use of the coarse FC fly ash resulted in an increase in the expansion as W/B of the FC mortar was rather high. For the immersion of the mortar in the sulfuric acid solution, the resistance to sulfuric acid attack was also improved with the incorporation of all fly ashes. In this case the coarser fly ash performed better. It is thought that the coarser fly ash particles with rougher surface would have a better bond with the cement matrix as well as occupying a larger volume and hence reduced the volume of the OPC and therefore resulted in a higher resistance to the sulfuric acid attack.

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