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EFFECTS OF FLY ASH PARTICLE SIZE ON STRENGTH OF PORTLAND CEMENT FLY ASH MORTARS

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ABSTRACT

Fly ashes do not have the same properties for different size fractions. It can be accepted that the effect of a fly ash on mortar strength is a combined effect of its size fractions. Therefore, it was concluded that by separating the size fractions and replacing cement with them, the combined bulk effect of a fly ash on strength can be better analysed. In this study, different size fractions of fly ash were used to replace cement partially in standard compressive strength mortars. We attempted to interpret the strength of Portland cement-fly ash mortars in terms of the chemical, minerological, morphological, and physical properties of different fly ash size fractions used. Strengths of the mortars were compared at 2, 7, 28, and 90 days. Also strength of mortars with all-in ash (original ash containing all the fractions) were estimated by using strength of mortars with size fractions and the suitability of this estimation was discussed. *© 1998 Elsevier Science Ltd*

Introduction

The utilization of fly ash as cement replacement material in concrete or as additive in cement introduces many benefits from economical, technical and environmental points of view. Depending on the burning temperature, coal type and some other factors fly ashes show different properties in different size fractions. In this study, combined effects of these different properties on the strength of fly ash incorporated mortars were investigated by using different size fractions separately. The object was to correlate overall effect of fly ash incorporation on strength to the effects of separate size fractions. One of the previous studies showed that granulometry of ash has important effect on mortar strength (1). Using this information, effects of changes in the granulometry of same ash on mortar strength were analysed in the present research. In another study, concrete stregths were correlated to fly ash addition amount and fineness (2). The study successfully formulised the stregth of concretes including coarse and fine fly ashes of similar chemical and mineralogical compositions. But this study was not concentrated on ash granulometry, as was the former one. The results have

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TABLE 1
Some of the material characteristics of the fly ashes used in the study.

	Ash HIGH	Ash LOW
MgO %	1.44	0.55
Al_2O_3 %	19.43	27.72
SiO_2 %	46.45	57.30
CaO %	12.69	2.24
Fe_2O_3 %	9.32	5.72
SO_3 %	4.80	0.26
K_2O %	1.66	3.68
Na_2O %	2.29	0.40
Loss on ignition %	1.11	1.12
Density g/cm^3	2.23	1.99
Above 125 μm sieve %	27.92	34.21
Above 90 μm sieve %	36.34	44.74
Above 63 μm sieve %	45.49	54.94
Above 45 μm sieve %	53.72	62.92
Minerals in the ash	Anhydrite, Hematite, Magnetite, Feldspat, Quartz, Glass	Quartz, Mullite, Glass

shown that the fly ash usability in concrete is related with its fineness. The idea of addition of fly ash size fractions to mortars was applied by Giergiczyn and Werynska also (3). Their results have yielded that high calcium fly ash showed great variability for various grain sizes. The study also gave that partial replacement of cement with finest size fraction resulted in minimum strength decrease with respect to mortars without any cement replacement.

Materials and Methods

A high lime (HIGH) and a low lime (LOW) fly ashes were used in this study. Their properties are given in Table 1. The Portland cement used was an ordinary Portland cement.

Fly ashes were sieved from the 125, 90, 63, and 45 μm sieve series by a sieve shaker and the materials retained on each sieve were used in the tests. As a result, six different size groups, including the all-in ash, were obtained for both of the ashes. These were: all-in ash, material retained on 125 μm sieve, material having size ranges 125–90, 90–63, and 63–45, and material passing 45 μm sieve. To investigate the effects of all the six size groups on the strength of fly ash incorporated mortars, characterisation of them by chemical analyses, and microscopy observations were carried out. Minerals in the ashes and the fractions were determined by XRD. For the strength tests, mixtures composed of 25% fly ash and 75% Portland cement, by weight, were prepared. The strength tests were carried out according to ENV 196–1 (4).

Results and Discussion

The chemical compositions of the size fractions of HIGH and LOW are given in Table 2. In Table 3; 2, 7, 28, and 90 day compressive strength values of the mortars with fractions or

TABLE 2
Chemical compositions of the size fractions of the ashes.

	Ash HIGH*						Ash LOW*					
	above 125	125–90	90–63	63–45	under 45	COV **	above 125	125–90	90–63	63–45	under 45	COV **
MgO %	1.52	1.21	1.32	1.48	1.56	0.10	0.55	0.56	0.57	0.55	0.56	0.02
Al_2O %	19.12	20.78	19.85	19.90	18.05	0.05	24.44	27.94	28.36	27.65	29.30	0.03
SiO_2 %	51.38	52.12	50.90	48.27	43.45	0.07	58.15	57.06	56.64	57.70	56.10	0.01
CaO %	12.00	10.61	11.77	12.46	13.47	0.09	2.12	2.24	2.14	2.27	2.10	0.04
Fe_2O_3 %	7.22	7.08	7.72	8.85	10.23	0.16	5.59	5.81	5.87	5.68	5.65	0.02
SO_3 %	2.25	2.20	2.63	3.52	7.16	0.59	0.22	0.25	0.20	0.25	0.25	0.10
K_2O %	1.47	1.36	1.45	1.52	1.84	0.12	3.65	3.63	3.74	3.60	3.75	0.02
Na_2O %	2.23	2.87	2.92	2.50	1.94	0.17	0.54	0.42	0.44	0.40	0.40	0.13
LOI*** %	2.04	0.87	0.68	0.72	1.48	0.51	1.07	1.36	1.17	1.04	1.05	0.12
Minerals in the fractions	Anhydrite, Hematite, Magnetite, Feldspat, Quartz, Glass						Quartz, Mullite, Glass					
	Mineralogical analyses by XRD were carried out for each fraction. As a result, it was seen that for both of the ashes minerals in each fraction contains the same minerals as the ash do.											

* Size fractions in μm.
** Coefficient of variation.
*** Loss on ignition.

all-in ashes are presented. As can be seen in the Table 3, HIGH incorporated mortars exhibit higher strength results than mortars with LOW at all the ages. This may be mainly due to the higher activity of HIGH resulting from mineralogical factors. For both of the ashes, as expected, the finer the size of a fraction used, the higher compressive strength results the tests yielded.

To analyse the changes in the strength values of the mortars with fractions, changes in the properties of the fractions were investigated. When the variation of the chemical composition of the fractions are considered, it can be concluded that LOW does not show composition changes. Therefore, it was concluded that the changes in the strength values of the mortars with the fractions of LOW were not caused mainly by the variations in the composition of the ash. For LOW, it was also seen that the size fractions do not show considerable changes when mineralogical analyses are considered. As a result, it was deduced that the changes in the strength of the mortars with different size fractions of LOW is accepted as mainly due to the particle size difference between the size fractions used. Thus, LOW can be a good example for observing the extent of the effect of particle size change of ash in the fly ash incorporated mortars. For the fractions of HIGH it was seen that other than particle size, chemical composition also changes from fractions to fractions substantially. Therefore, HIGH can be accepted as the opposite case considering the changes in the properties of the fly ash size fractions.

To understand the applicability of a calculation method of the strength of all-in ash added mortars by using the strength data of the mortars with fractions, the particle size distribution data given in Table 1 was used. Through the help of the information in this table, the amount of each fraction in the all-in ashes were determined (given in Table 4).

TABLE 3
Compressive strength results of the mortars.

		2 Day (N/mm^2)	7 Days (N/mm^2)	28 Days (N/mm^2)	90 Days (N/mm^2)
25% HIGH* + 75% PC 32.5*	All-in Ash	27.6	36.7	46.7	55.7
	Above 125 μm	19.2	26.6	31.2	33.2
	[125-90] μm	22.6	27.6	35.0	38.4
	[90-63] μm	24.8	31.3	35.4	42.6
	[63-45] μm	26.6	35.1	41.4	47.5
	Under 45 μm	32.0	43.0	55.8	64.6
*25% LOW + *75% PC 32.5	All-in Ash	23.5	33.2	39.6	47.4
	Above 125 μm	17.9	24.4	26.7	29.9
	[125-90] μm	21.6	29.2	32.0	37.1
	[90-63] μm	22.6	29.6	34.9	40.6
	[63-45] μm	23.8	33.5	37.4	46.8
	Under 45 μm	26.6	37.3	43.4	57.2
100% PC 32.5		38.0	44.4	51.6	58.2

* Weight percentages.

This amount is used as weight for the strength value of each fraction for the calculation of all-in ash added mortar strength. By application of this idea, the strengths of the mortars with all-in ashes were tried to be estimated. The calculated results as percentages of the test results are presented in Table 5.

As can be seen in Table 5, for both of the ashes, all the calculated results are lower than the actual test results. One of the reasons for this is thought to be the effect of grading. As the fractions are of uniform particle size distribution, the porosity of the mortars with them is higher than the mortars with all-in ashes. In other words, as in the original ash added mortars different size fractions fill the pores, and higher strength values than expected have been obtained. As a second result, a closer study on these values shows that, the calculation estimates the actual test values more closely at earlier ages. For instance, as given in Table 5, for both of the ashes the calculated strength results showed 96% of the actual values at 2 days, whereas at 90 days the calculations remarkably underestimated the actual strength of the mortars with all-in ash (about 10% lower than

TABLE 4
Percentage of the size fractions in the original ashes.*

	Ash HIGH					Ash LOW				
	above 125	125–90	90–63	63–45	under 45	above 125	125–90	90–63	63–45	under 45
Amount %	27.92	8.42	9.15	8.23	46.28	34.21	10.53	10.20	7.98	37.08

* Size fractions in μm.

TABLE 5
The estimated compressive strength values for the mortars with all-in ash as percentage of the actual test results.

		2 Day	7 Day	28 Day	90 Day
Ash HIGH	Mortar with all-in ash ACTUAL TEST RESULTS (N/mm^2)	27.6	36.7	46.7	55.7
	Mortar with all-in ash CALCULATED VALUE as percentage of the actual test result (%)	96	96	94	90
	Mortar with all-in ash ACTUAL TEST RESULTS (N/mm^2)	23.5	33.2	39.6	47.4
Ash LOW	Mortar with all-in ash CALCULATED VALUE as percentage of the actual test result (%)	96	93	89	91

The percentages in Table 5 were calculated by the expression below for 25% weight basis cement replacements with original fly ashes in mortars;

$$CV = \frac{\sum A \times B}{C}$$

where *CV* is the calculated compressive strength as percentage of the test value for mortars with all-in ash; *A* is the amount of the particular size fraction in all-in ash percentage; *B* is the compressive strength of the mortar with that particular ash fraction; and *C* is the compressive strength of the mortars with all-in ash.

the test results). This means that the size fractions in the all-in ashes show higher activity with time than the same fractions by themselves. Other than the grading effect, this may be a result of the activating behaviour of the very fine particles. Fine particles behave as nucleus initiating and accelerating the hydration reactions. This effect is known to be on clinker particles but it seems that hydration of coarse ash particles is also positively affected. However, during the time of hydration concerned (90 day), fine particles hardly promote the hydration of coarse particles as the pozzolanic reaction is very slow. As a result, the positive effect of fine particles on hydration of clinker particles can be accepted as another reason for obtaining lower strength results by the calculation based on the addition of separate fraction effects. In other words, clinker particles behave in a more activated manner due to the presence of fine ash particles, and this causes the widening gap between the calculated and actual strength values with time.

When the strength results are expressed as percentage of the strength of the original ash added mortars at the same age, as shown in the Table 6, it can be seen that as a general tendency, the difference between the strengths of the mortars with all-in ash and the mortars with the fractions widens with aging for coarse fractions. This can be explained by the reasons mentioned before also. It is a well-known behavior for reactive materials that very fine particles are responsible for early age strength. Thus all-in ash added mortars have higer early age strength results than the mortars with coarse fractions since they contain fine particles also. When the fine particles are

TABLE 6
Compressive strength results as percentage of the strengths of original ash added mortars.

		2 Day (%)	7 Days (%)	28 Days (%)	90 Days (%)	Tendency with time
25% Ash HIGH + 75% PC 32.5	All-in Ash	100	100	100	100	-
	Above 125 μm	70	72	67	60	(↓)
	[125–90]	82	75	75	69	(↓)
	[90–63]	90	85	76	76	(↓)
	[63–45]	96	96	89	85	(↓)
	Under 45 μm	116	117	119	116	(↔)
25% Ash LOW + 75% PC 32.5	All-in Ash	100	100	100	100	_
	Above 125 μm	76	73	67	63	(↓)
	[125–90]	92	88	81	78	(↓)
	[90–63]	96	89	88	85	(↓)
	[63–45]	101	101	94	99	(↔)
	Under 45 μm	113	112	110	121	(↔)

consumed with time, the coarse particles come into scene for continuation of the strength gain in mortars with all-in ash. However, for the mortars with coarse fractions only, this long term strength gain is not as high as in the mortars with all-in ashes.

Conclusion

1. The strength of all-in ash added mortars can be found by a calculation based on the strengths of mortars with size fractions of the same ash by using the amount of the fractions in the all-in ash as weight. However, this method slightly underestimates the strength value of original ash added cements.
2. The estimation yields closer results to the actual test values at earlier ages.

Also, on the example of LOW, the actual pure effect of particle size on the compressive strength of mortars was observed since fractions of this ash do not show any considerable difference in chemical and mineralogical composition. For further evaluation of the effects of size fractions on strength, also tests on concrete specimens should be carried out.

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