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Influence of fly ash and its mean particle size on certain engineering properties of cement composite mortars

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Abstract

An experimental investigation on the effects of incorporating large volumes of fly ash on the early engineering properties and long-term strength of masonry mortars is reported. The effect of fly ash and its mean particle size (PD) on the variation of workability and strength has been studied. It was found that fly ash and its mean particle size play a very significant role on the strength of masonry mortars. It has been observed that the early-term strength, except the mortars incorporating coarse fly ash (CFA), was slightly influenced by the replacement with fly ash. The long-term strength (both the bond strength and the compressive strength) will significantly increase, especially for the bond strength of mortars incorporating coarse fly ash. It was also found that the bond strength significantly increased as the mean particle size of fly ash decreases *after 28 days curing*. However, the 7-day strength was little influenced by fly ash particle size. The fluidity of composite mortar enhanced due to replace cement and lime with fly ash, and the mean PD of fly ash significantly influenced the workability.

Keywords: Fly ash; Mean particle size; Masonry mortars; Workability; Bond strength; Compressive strength

1. Introduction

The early age properties required are water retention, workability, plasticity and adhesion to allow the mortar to possess good working properties such as the ease of spreading, proper filling of joints and also to provide a water resistant crack-free smooth surface. At later ages, strength becomes the main criterion to sustain the imposed load of the structure. Portland cement based mortars though harden rapidly and attain high strength but possesses a relatively poor early age properties. In composite mortars, there is a common practice to incorporate lime along with Portland cement to improve the early age properties. However, once the setting and hardening has taken place, lime plays little role on the later age strength of mortars, as it harden through the slow process of carbonation, i.e. by the chemical action of lime with atmospheric carbon dioxide forming insoluble carbonate. The process of carbonation is very slow and takes place from surface inwards. Fly ash has little cementing property when only water is added [1], its reactivity could be activated by OH^- [2,3], in ordinary Portland concrete, the pozzolanic reaction is very slow due to the low OH^- content. The replacement of part of cement and lime with fly ash in cement–lime mortar will consume a mass of calcium hydroxide (lime), at the same time the pozzolanic reaction will be activated due to the high OH^- content in mortars. In this paper, the main aim was to determine whether the use of fly ash as replacement for 30% of cement and for 50% of lime in cement–lime mortar has a significant influence on the properties of mortars.

Fly ash is commonly used in concrete because it may improve durability of concrete [4], however, fly ash addition in concrete should meet the ASTM C618 requirements, and unclassified fly ash cannot be used to replace cement due to its low chemical reactivity [5]. If large amounts unclassified

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Table 1
Chemical and physical properties of cement and fly ash

Chemical analysis (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	LOI	Specific surface, Blaine (m^2/kg)	Relative density
Cement	19.5	4.4	6.22	65.9	1.5	1.09	0.30	1.43	462	3.15
Fly ash	53.9	28.5	8.7	4.7	1.3	0.30	0.48	2.12	–	2.2

fly ash can be replaced without significant damage to mortar characteristics, the replacement unclassified fly ash in cement–lime mortar has both environmental and economical advantages. The other main aim of this investigation was to determine whether the use of unclassified fly ash as replacement in cement–lime mortar has a significant influence on the properties of mortars.

At the same time, in this paper, the influence of mean PD of fly ash on the properties of mortars also was studied. Assessments of the mixes were based on short- and long-term performance of mortar. These included the bond strength of mortar-to-brick, and the compressive strength development to 120 days.

Ferraris et al. [6] reported that the addition of certain type of fly ash enhances the workability of concrete. In order to investigate the influence of incorporating fly ash on the workability of mortars, the fluidity of mortars with or without fly ash was also tested.

2. Materials

The cement was a Portland cement whose properties are described in Table 1. The fine aggregates were standard natural sand with a specific gravity of 2.50. The fly ash properties are also given in Table 1. The mean particle diameter (PD) of fly ash was measured by using a laser diffraction particle size analyzer. Four different kinds fly ash (Table 2), all from the same plant (Shantou Huaneng Power Plant), were tested. FA has a standard mean PD, which is separated through rejecting coarse fly ash and fine fly ash. Coarse fly ash (CFA) was a coarse ash that is usually rejected, as it does not meet the ASTM C618 requirements for particle size. Fine fly ash (FFA) is a finer form of ash obtained by separation from a ground fly ash (grinding 20 min) by using a standard sieve (45-μm sieve). Ultrafine fly ash (UFA) is an ultrafine ash obtained by still more rigorous separation (grinding 40 min). The rations of different size particles are presented in Table 2.

Table 2
Ratios of size particles of fly ash in the mix

Mix pozzolana	Name/Mean PD (um)				Average size (um)
	CFA/18.8	FA/9.1	FFA/5.4	UFA/2.8	
CFA	1	0	0	0	18.8
FA	0	1	0	0	9.1
FFA	0	0	1	0	5.4
UFA	0	0	0	1	2.8
MCU	0.5	0	0	0.5	10.8
MCA	0.5	0	0.5	0	12.1
MCF	0.5	0.5	0	0	13.95
MAA	0	0.5	0.5	0	7.25
MAU	0	0.5	0	0.5	5.94
MFU	0	0	0.5	0.5	4.1
MCFU	0.25	0.25	0.25	0.25	9.025

3. Experimental program

Masonry mortars were mixed using a large blender (4 L). Aggregate and cementitious materials were blended for 2 min. Water and lime paste were then added and mixed for 5 min at low speed and finally for 1 min at high speed, and the composition of mortars is shown in Table 3. One part of the mortars was molded in 10 cm cubes and demolded 72 h later. The pastes were slightly pressed to remove any air bubbles and voids.

3.1. Fluidity

The fluidity of mortar was measured by the flow table test. The compositions of mortars are shown as follows:

* water/binder ratio=0.61 (binder=cement+fly ash);
* sand used in mortars is shown in Table 3;
* lime paste has a flow of 110 mm;
* dosages of mineral admixtures are shown in Table 3.

3.2. Bond strength

The ability of mortar to have a good bond and adhesion with the brick is determined by its bond strength and is measured by the force necessary to separate the masonry unit from the mortar. The bond strength of mortar test method schematic was shown in Fig. 1. A saturated half brick was taken and a half inch thick layer of the mortar prepared at 100±5 mm flow was applied. Another saturated half brick was placed over this and 8.0 kg mass was applied for 2 min. The samples were cured at 95% relative humidity and were determined after 7, 28, 56 and 120 days curing. Bond strength was determined by the force in kg required to separate out the bricks.

3.3. Compressive strength

The compressive strength of the various compositions was determined on 10 cm cubes at 100±5 mm flow as per standard method. The cubes were cured at 27±2 °C temperature and 95% relative humidity for 7 days and then

Table 3
Mix proportions for different groups of mortar specimens (on weight)

No.	Cement	Lime	Sand	CFA	FA	FFA	UFA	MCU	MCA	MCF	MAA	MAU	MFU	MCFU
1	1	1	6	0	0	0	0	0	0	0	0	0	0	0
2	0.7	0.5	6	0.8	0	0	0	0	0	0	0	0	0	0
3	0.7	0.5	6	0	0.8	0	0	0	0	0	0	0	0	0
4	0.7	0.5	6	0	0	0.8	0	0	0	0	0	0	0	0
5	0.7	0.5	6	0	0	0	0.8	0	0	0	0	0	0	0
6	0.7	0.5	6	0	0	0	0	0.8	0	0	0	0	0	0
7	0.7	0.5	6	0	0	0	0	0	0.8	0	0	0	0	0
8	0.7	0.5	6	0	0	0	0	0	0	0.8	0	0	0	0
9	0.7	0.5	6	0	0	0	0	0	0	0	0.8	0	0	0
10	0.7	0.5	6	0	0	0	0	0	0	0	0	0.8	0	0
11	0.7	0.5	6	0	0	0	0	0	0	0	0	0	0.8	0
12	0.7	0.5	6	0	0	0	0	0	0	0	0	0	0	0.8

in limewater for up to 120 days. These cubes were dried 24 h prior to testing for every mix at the required age, and the average strength of six specimens was used as the measure of strength.

4. Results and discussion

4.1. Fluidity property

Fig. 2 shows the influence of fly ash and its mean particle size (PD) on the fluidity of mortar. Those tests were done at a W/C ratio of 0.61. It is indicated that the addition of fly ash can enhance the flow property of mortars, and UFA (No. 5) is optimal for the fluidity properties. The most common reason for good workability is that the addition of fine powers decreases the water demand due to the spherical particles easily roll over one anther and at the same time, the spherical particles minimize the particle's surface to volume ratio (which also called the ball bearing effect).

In Fig. 3, the flow measurements for those modified composite mortars are plotted against the mean particle size (PD) of fly ash. It has been observed that as the mean PD of fly ash particles increases, the flow decreases to a certain value and then gradually increases. It is clear that the highest flow is obtained at a mean PD of 2.8 μm, this value corresponds again to UFA (No. 5). It also seems that the lowest flow is reached at a mean PD of about 9±3 μm; these values correspond again to FA (No. 2). This result seems to indicate an optimum and a pessimum PD, with the optimum at 2.8 μm and the pessimum at 9±3 μm.

4.2. Bond strength

The bond strengths of cement–lime mortar and those modified composite mortars are given in Table 4. From this Table 4, it is clear that the bond strength development for the mortar with coarse fly ash (CFA) needs a much longer period of time than that of mortar without fly ash. However, the bond strength of other modified composite mortars develops

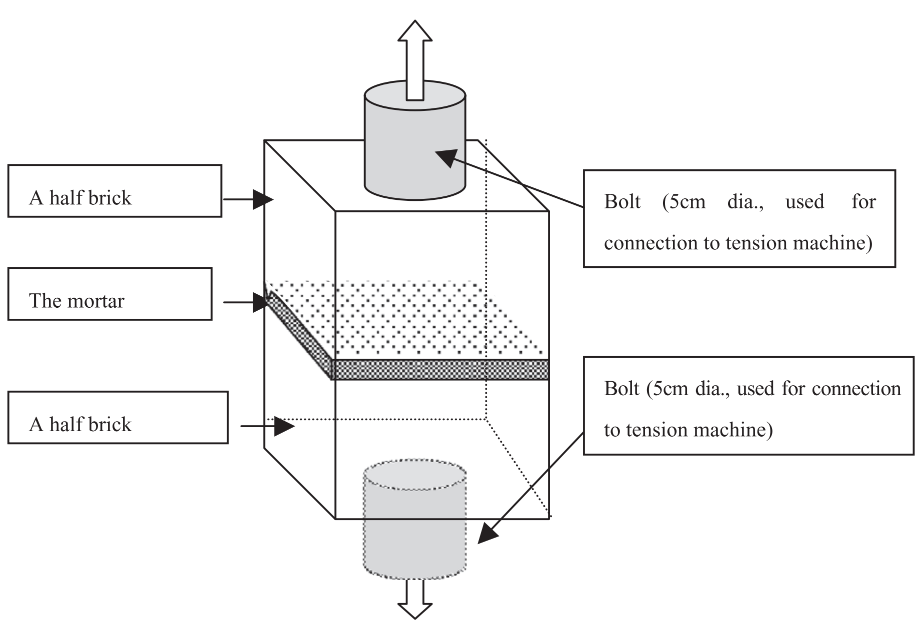

Fig. 1. Specimen for bond strength tests.

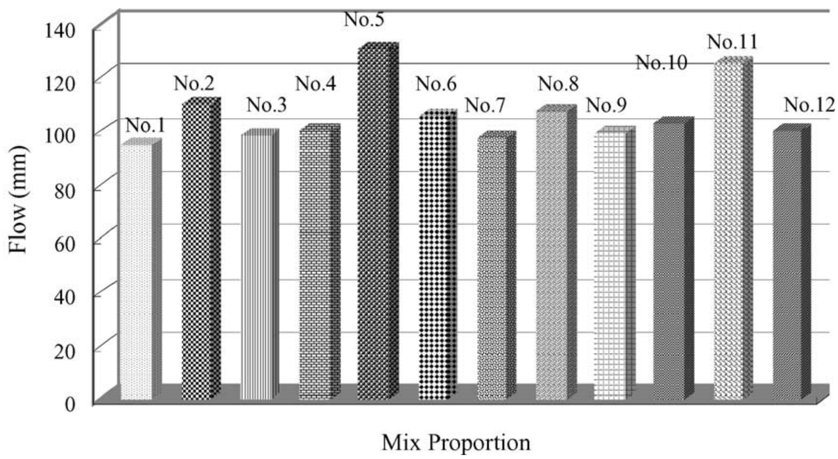

Fig. 2. Fluidity of mortars with and without fly ash.

faster than that of mortar without fly ash, even at 7 days, the bond strength of modified composite mortar with ultra-fine fly ash (No. 5) is higher than that of controlled mortar (No. 1). The 120-day bond strength of modified composite mortars is almost 1.5 times of that of the cement–lime mortar, even for mortar only incorporating coarse fly ash, the bond strength is higher than that of cement–lime mortar.

Table 4 shows the strength gain of the mortars from 28 to 120 days. Though the control mortar (No. 1) obtains high early-term bond strength, its strength gain is the lowest (22.4%) during this period. The bond strength of modified composite mortars incorporating FFA (No. 4), UFA (No. 5), MAU (No. 10), and MFU (No. 11) obtains high early term bond strength, and their strength gains are also high. The early-term bond strength of other modified composite mortars is lower than that of control mortar, but their strength gain from 28 to 120 days is remarkably higher than that of controlled mortar. For No. 2, modified composite mortar incorporating CFA though has the lowest strength before 56 days, its strength gain is the highest at the end test age.

The effect of the mean particle size (PD) of fly ash on the bond strength is shown in Fig. 4. It is clear that the bond strength of modified composite mortar is influenced by fly ash mean PD, the bond strength of mortars increases as the size of fly ash decreases. However, the effect of fly ash PD on the bond strength varies with the test age. At the age of 7 days, the bond strength was slightly influenced by the fly ash size, which may due to cement that plays a main role on producing bond force at this period. Whereas after 28 days curing, the bond strength was notability influenced by the mean particle size (PD) of fly ash.

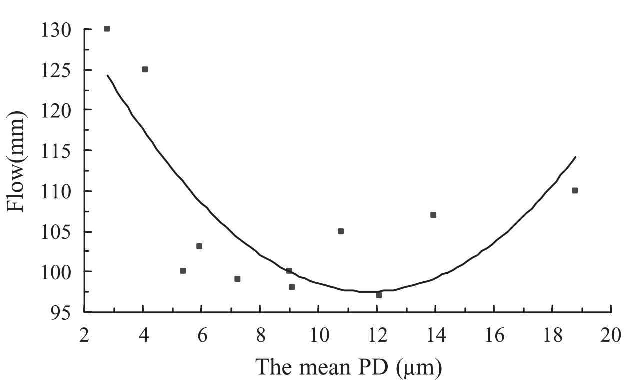

Fig. 3. Influence of mean PD on the flow properties of mortar.

4.3. Compressive strength

The compressive strengths of cement–lime mortar and modified composite mortars are given in Table 5. From this table, it is clear that the compressive strength development for the mortar with coarse fly ash (CFA) needs a much longer period of time than that of mortar without fly ash. However, the compressive strength of other modified composite mortars develops faster than that of mortar without fly ash, even at 7 days, the compressive strengths of modified composite mortar with UFA (No. 5) and mortar with MFU (No. 11) are higher than that of controlled mortar (No. 1). The 120-day compressive strength of modified composite mortars is higher than that of the cement–lime mortar.

Table 5 shows the strength gain of the mortars from 28 to 120 days. Though the control mortar (No. 1) obtains high

Table 4
Test results on bond strength of mortars

No.	Fly ash size	Bond strength, kg/m^2				Strength gain from 28 to 120 days, kg/m^2	Percent strength gain
		7 days	28 days	56 days	120 days		
1	–	0.85	1.25	1.41	1.53	0.28	22.4
2	18.8	0.61	1.10	1.48	1.68	0.68	61.8
3	9.1	0.77	1.29	1.59	1.98	0.69	53.5
4	5.4	0.81	1.55	1.88	2.15	0.6	38.7
5	2.8	0.86	1.70	1.99	2.21	0.51	30
6	10.8	0.76	1.30	1.64	1.92	0.62	47.7
7	12.1	0.73	1.26	1.53	1.82	0.56	44.4
8	13.95	0.68	1.2	1.49	1.78	0.58	48.3
9	7.25	0.79	1.35	1.65	2.08	0.73	54.1
10	5.94	0.82	1.6	1.8	2.18	0.58	36.3
11	4.1	0.84	1.67	1.9	2.25	0.58	34.7
12	9.025	0.8	1.41	1.72	2.05	0.64	45.4

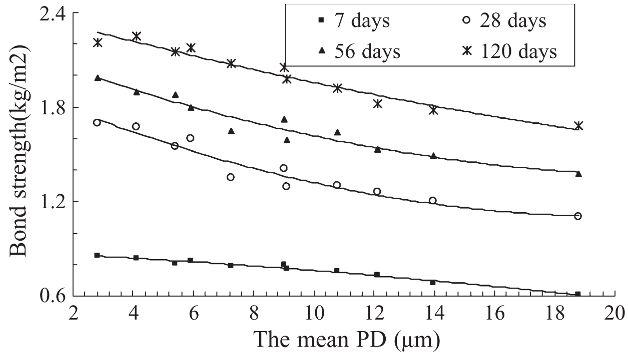

Fig. 4. At different test ages, the influence of fly ash mean PD on the bond strength in modified composites mortars.

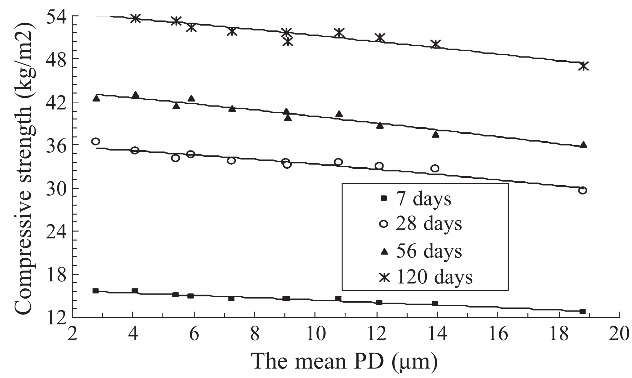

Fig. 5. At different test ages, variation of compressive strength with fly ash mean PD in modified composites mortars. (a) At the age of 7 days, (b) at the age of 28 days, (c) at the age of 120 days.

early-term compressive strength, its strength gain is the lowest (24.8%) during this period. The compressive strength of modified composite mortars incorporating FFA (No. 4), UFA (No. 5), MAU (No. 10), MFU (No. 11) obtains high early term compressive strength, and their strength gains are also high. The early-term compressive strength of other modified composite mortars is lower than that of control mortar, but their strength gains from 28 to 120 days are remarkably higher than that of control mortar. For No. 2, modified composite mortar incorporating CFA though has the lowest strength before 56 days, its strength gain is the highest at the end test age.

The effect of fly ash size on the compressive strength is shown in Fig. 5. It is clear that the compressive strength of all modified composite mortars is slightly influenced by the size of fly ash, the compressive strength of mortars slightly increases as fly ash PD decreases.

4.4. The comparison of bond strength with compressive strength

In order to enlighten the different effect of the addition of fly ash and its mean PD on the bond strength and on the compressive strength, the ratio of strength (ΔR) was calculated using the RET equation. The RET equation gives a relation between the strength of mortars incorporating fly ash and the strength of control mortar without fly ash at the same test age. The RET equation in use is

$$\Delta R = (R_i - R_o)/R_o$$

where R_i is the strength (bond strength or compressive strength) of modified composite mortars with fly ash; R_o is the strength of cement–lime mortar. The ΔR of different mixtures at the different test age are shown in Fig. 6a–c.

According to the measurements presented in Fig. 6b and c, at the 120- and 28-day test age, the bond strength shows significantly higher ΔR than the compressive strength when the mean PD of fly ash is less than 10 um; at the 7-day test age, the bond strength shows lower ΔR than the compressive strength at the mean PD of fly ash from 2 to 20 μm. As shown in Fig. 6a–c, the ΔR of bond strength and the ΔR of compressive strength decrease as the mean PD of fly ash increases. The effect of mean PD of fly ash on ΔR of bond strength and on that of compressive strength is different, at the same test age, the mean PD of fly ash shows higher influence on the bond strength than on the compressive strength.

Table 5
Test results on compressive strength of mortars

No.	Fly ash size	Compressive strength, kg/m^2				Strength gain from 28 to 120 days, kg/m^2	Percent strength gain
		7 days	28 days	56 days	120 days		
1	–	15.5	32.7	37.5	40.8	8.1	24.8
2	18.8	12.8	29.8	36	48	18.2	61.1
3	9.1	14.5	33.2	39.9	50.5	17.3	52.1
4	5.4	15	34	41.5	53.2	19.2	56.4
5	2.8	15.6	36.4	42.6	54.7	18.3	50.3
6	10.8	14.6	33.5	40.3	52.4	18.9	56.4
7	12.1	14	33	38.8	51.7	18.7	56.7
8	13.95	13.8	32.6	37.5	50	17.4	53.4
9	7.25	14.6	33.7	41	51.9	18.2	54
10	5.94	15.2	34.6	42.5	52.3	17.7	51.2
11	4.1	15.6	35.1	43	53.6	18.5	52.7
12	9.025	14.5	33.6	40.8	51.7	18.1	53.9

5. Conclusions

The fluidity of mortars results indicates that the workability of mortars will be enhanced due to the incorporating fly ash, especially incorporating ultra-fine fly ash. The mean PD of fly ash will significantly influence the flow of mortars, as the mean PD increases, the flow decreases down to certain value and then gradually increases. The highest flow is obtained at a mean PD of 2.8 μm; and the lowest flow is reached at a mean PD of about 9±3 μm.

Both the bond strength and the compressive strength results show that the strength development is significantly affected by the replacement with fly ash. Based on the results of this investigation, it can be concluded

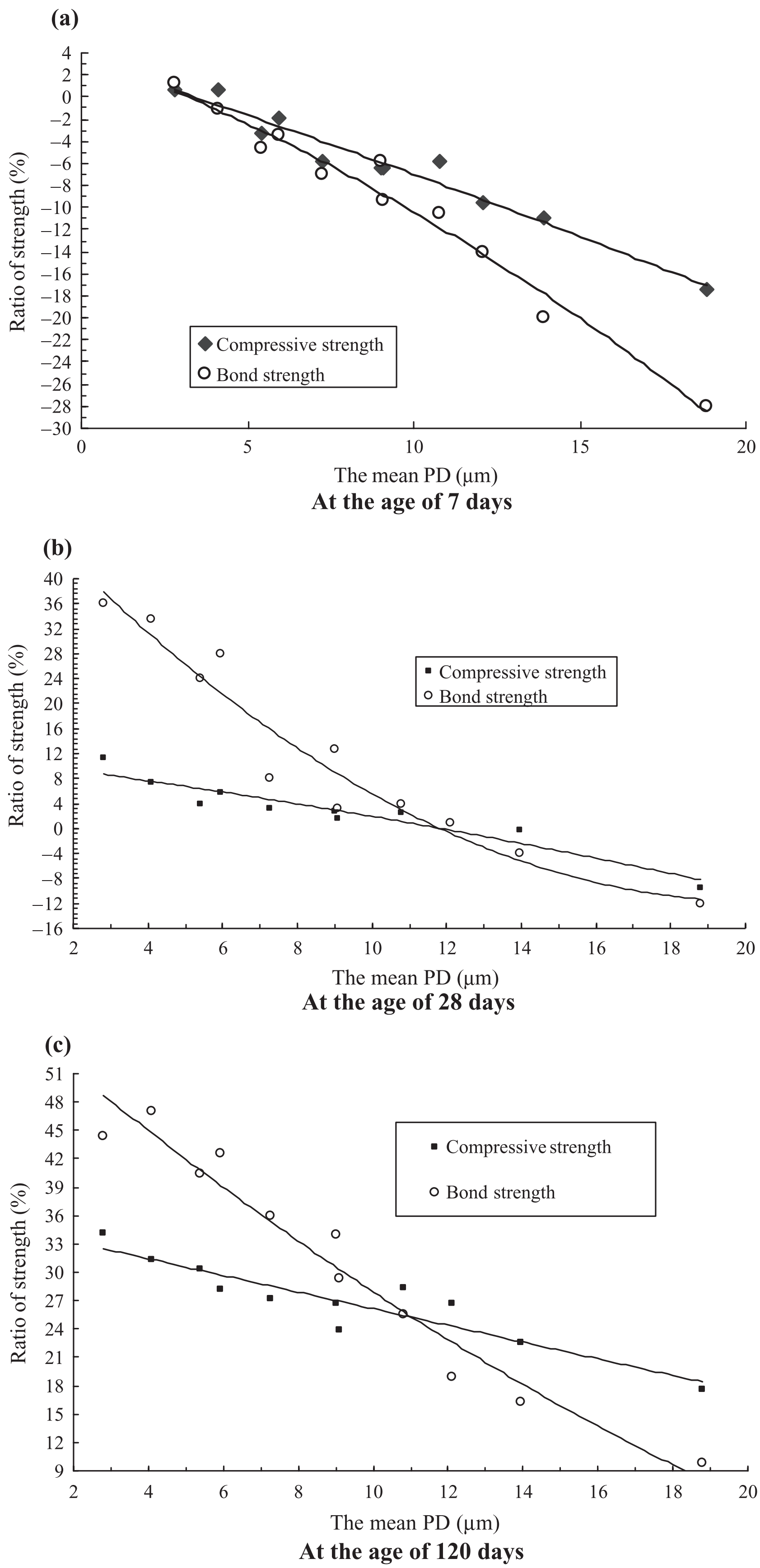

Fig. 6. At different test ages, the effect of fly ash mean PD on the ratio of bond strength and on the ratio of compressive strength.

that replacing cement and lime with fly ash will significantly improve the long-term strength of well-cured mortars.

The results presented in this paper show that although the mortars with coarse fly ash contents might need a longer period of time to reach their ultimate strength, this strength could be higher than the ultimate strength that can be achieved using only cement and lime. The mixing coarse fly ash with fine and ultra-fine fly ash can significantly increase the later-age strength and does not significantly decrease the early-term strength of mortars. At the same time, the mortars with coarse fly ash contents have the highest strength gain and the control has the lowest strength gain.

Both the bond strength and the compressive strength were affected by the mean PD of fly ash, the strength decreases as the mean PD increases, especially at the age of 28, 56 and 120 days. Fly ash and its mean size show higher influence on the bond strength than on the compressive strength.

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