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A new way to increase the long-term bond strength of new-to-old concrete by the use of fly ash

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Abstract

The short-term and long-term bond strengths of new-to-old concrete were experimentally investigated with an emphasis on the influence of new concretes and binders. These new concretes included ordinary Portland cement concrete, expansive concrete and high-volume fly ash concrete, while the binders included pure cement paste (C-binder), expansive binder (E-binder) and fly ash mortar (F-binder). The results showed that the short-term bond strength of all specimens with fly ash concrete was lower than that with ordinary Portland cement concrete, which in turn was lower than that with expansive concrete. The bond strength of the specimens with F-binder was the lowest at the age of 7 days. However, the long-term bond strength of all specimens with added fly ash was the highest and strength losses were observed in the specimens repaired with expansive concrete or E-binder at the age of 3 years. The microstructure of the transition zone with F-binder was also studied by using both scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) at the ages of 28 days and 1 year, respectively.

Keywords: Bond strength; Fly ash; SEM; Microstructure

1. Introduction

Good bond is one of the main requirements for successful repair [1–3]. An investigation [4] on old concrete repair for some bridge decks underneath showed that 10% of the repaired areas were found to be hollow after 1 year. One more year later, this figure increased to 30–35%. These faulty sections were then repaired very carefully, but within only a few weeks shallow spots appeared again. How to improve the durability of the repaired concretes has drawn great attention from research workers. It has been indicated that the interface between new and old concrete is the weakest section in the repaired concrete [5], and that the binder is a vital factor [6,7], which affects the performance of the interfacial transition zone. It is reported that the use of silica fume or fly ash can change the microstructure of the transition zone and, as a result, increase the bond strength because of a microfiller effect or the prevention from growing calcium hydrate crystals [5,8,9]. The shrinkage property of new concrete is also known to have an effect on the bond strength; therefore, the replacement of cement constituents with expansive agent has been investigated as a modification method to achieve a higher bond strength [7,10].

In this study, the addition of high-volume fly ash to both the new concrete and the binder to enhance the bond strength is investigated. The failure modes of the specimens repaired with the fly ash concrete and F-binder are studied. As a comparison, the bond strengths and the failure modes of the specimens repaired with ordinary Portland cement concrete, expansive concrete, C-binder and E-binder are also presented. In order to understand the influence of various new concretes on the property of the repaired concrete, the microstructure of the transition zone between the new concretes and F-binder was observed under scanning electron microscope (SEM) with an energy dispersive spectroscopy analyzer (EDS).

2. Experimental program

2.1. Materials

The cement used in the mixes was ordinary Portland cement. A Class I (Chinese Standard) fly ash from Shantou

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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)	28 days compressive strength (MPa)
Cement	19.5	4.4	6.22	65.9	1.5	1.09	0.30	1.43	462	45.9
Fly ash	52.6	18.1	8.2	15.7	1.93	0.30	0.48	3.6	625	–

Huaneng Power Plant was selected for this work. Both the chemical and physical properties of the cement and fly ash are presented in Table 1. The coarse aggregate was crushed limestone with a maximum size of 20 mm. The fine aggregate was river sand with a fineness modulus of 2.35. U-type expansive agent from Tianjing, China was selected for this work. The main component of U-type expansive agent is calcium sulphoaluminate. The mix proportions of binders are presented in Table 2. The composition of ordinary Portland cement concrete, expansive concrete, fly ash concrete and old concrete is presented in Table 3.

2.2. Bond strength test

2.2.1. Split strength test

Split strength tests of old concrete were carried out on cube specimens (100 mm) at the age of 3 months, according to Chinese Standard GB-8185, and the average strength of five specimens was used as an index. Then, those split $100 \times 100 \times 50$ mm^3 old concretes were immersed in water and, after saturation, the $100 \times 100 \times 50$ mm^3 old concretes were taken out and placed in plastic mold ($100 \times 100 \times 100$ mm^3). Binders were cast on the split surface of old concrete with 1–2 mm thickness and, 30 min later, new concrete was placed. A vibrating table was used to ensure good compaction. Then the surface of concrete was smoothed, and a wet cloth was used to cover the concrete until the specimens were demolded 1 day after casting. Then these specimens were wet-cured by covering with wet burlap for 7 days, followed by storing in laboratory before test. The bond strength of these samples was measured by using split method (Fig. 1) after curing for 28 days and 1 year, respectively. For the purpose of comparison, the split strength of new concretes was also tested at the ages of 28 days and 1 year, respectively. The 28-day strengths of fly ash concrete, Portland concrete and expansive concrete are 3.119, 3.438 and 4.313 MPa, respectively, while the 1-year strengths of fly ash concrete, Portland concrete and expansive concrete are 5.442, 5.223 and 5.128 MPa.

2.2.2. Pull-off strength test

Six beams, $200 \times 250 \times 4000$ mm, were cast for pull-off strength test (the experimental scheme are summarized in Table 4. In this table, PFF: old concrete/F-binder/fly ash concrete, PFE: old concrete/F-binder/expansive concrete, PFC: old concrete/F-binder/new control Portland cement concrete, PEF: old concrete/E-binder/fly ash concrete, PEE: old concrete/E-binder/expansive concrete, PEC: old concrete/E-binder/new control Portland cement concrete). These specimens were wet-cured by covering with wet burlap for 7 days, followed by storing in laboratory for 2 months before repairing. A wire brush was used to roughen the surface of the beams. When loose concrete and dust had been removed, the surface was washed with sprinkling water. The specimens were then placed in specially prepared wooden molds ($200 \times 300 \times 4000$ mm). A layer (about 1 mm thick) of binders was coated on the surface of the substrate and, 30 min later, the repair concrete was applied. The repaired portions for all of the beams were wet-cured by covering with wet burlap for 7 days, followed by storing in laboratory before test. The bond strength of these samples was measured by using pull-off method, which was carried out after curing for 7, 28, 120 days, 1 year and 3 years, respectively. The average strength of five specimens was used as an index. Cores of 50 mm in diameter and 70 mm in height were drilled through the overlay down into the base

Table 2
Mix proportions of binders

Binder type	Cement	Water	Sand	Fly ash	U-type expansive agent	Superplasticizer dosage[a]
C-binder	1	0.4	–	–	–	0.5
F-binder	0.6	0.4	1	0.4	–	1.5
E-binder	0.9	0.4	–	–	0.1	0.5

[a] Dosage given as percent of total binder content by mass.

Table 3
Different types of mixture proportions used

Mixture type	Old concrete	New control Portland cement concrete	Fly ash concrete	Expansive concrete
Cement (C), kg/m^3	432	432	252	398
Fly ash (F), kg/m^3			168	
Expansive agent (E), kg/m^3				44
Sand, kg/m^3	676	676	750	676
Coarse aggregate, kg/m^3	1102	1102	1020	1102
Water, kg/m^3	190	190	190	190
Superplasticizer, kg/m^3			4.2	
W/(C + F/E)	0.44	0.44	0.44	0.44
Slump, mm	40	40	40	40

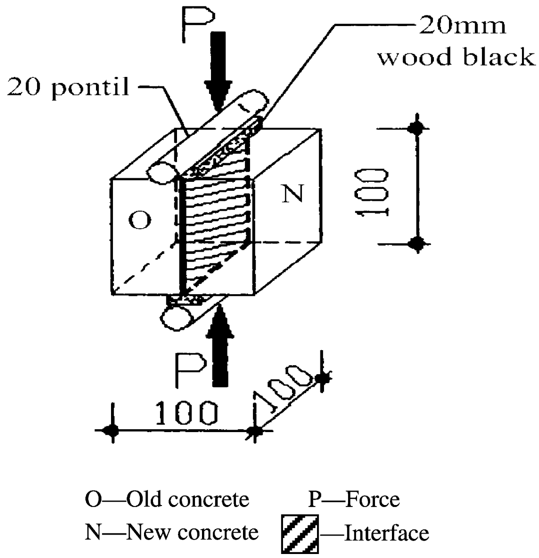

Fig. 1. Specimen for split strength tests.

Fig. 2. Specimen for pull-off strength tests.

concrete, and the pull-off apparatus DYNA was used to test the bond strength (Fig. 2).

2.3. SEM analysis

Though there are two interfaces in the transition zone, one between the old concrete and the F-binder and the other between the F-binder and the new concrete, only the interface between the F-binder and the new concrete (Fig. 3) was observed because the new concrete has little influence on the one between the old concrete and the F-binder. Three samples with a size of $1 \times 1 \times 1$ cm^3 were taken from each repaired concrete at the age of 28 days, and another three samples were taken at the age of 1 year. All these samples were put into absolute alcohol before test. The interface between the new concrete and the F-binder at the age of 28 days was observed by the H-1030 SEM with an EDS analyzer, and the interface at the age of 1 year was observed by the S-450 SEM. The samples were gold-coated before examination in the SEM.

3. Failure modes of specimens tested

In the bond strength tests, failures occurred in the four different regions (Fig. 4): (1) in the interfacial transition zone between the new and the old concrete, named as mode A; (2) in the new concrete near interface, named as mode B; (3) in the old concrete near interface, named as mode C; (4) from the old concrete to the new concrete throughout the interfacial transition zone, named as mode D. The failure modes of these specimens under split strength test and pull-off strength test are shown in Tables 5 and 6, respectively.

Table 4
Test section

Mix codes	Binders	New concretes
PFE	F-binder	Expansive concrete
PFC	F-binder	Portland cement concrete
PFF	F-binder	Fly ash concrete
PEE	E-binder	Expansive concrete
PEC	E-binder	Portland cement concrete
PEF	E-binder	Fly ash concrete

4. Effect of new concretes and binders on the bond strength

4.1. Split strength

Many researchers reported that the development of the strength was slowed in the early curing period by adding fly ash because the overall pozzolanic reaction was slow. However, the strength was enhanced after weeks. The reason is that the pozzolanic reaction of fly ash with calcium hydroxide (CH) may reduce the content of CH in concrete and increase its density. The present results seem to follow this finding. As can be seen from Figs. 5 and 6, when the same binder is used, the bond strength of the specimens repaired with fly ash concrete at the age of

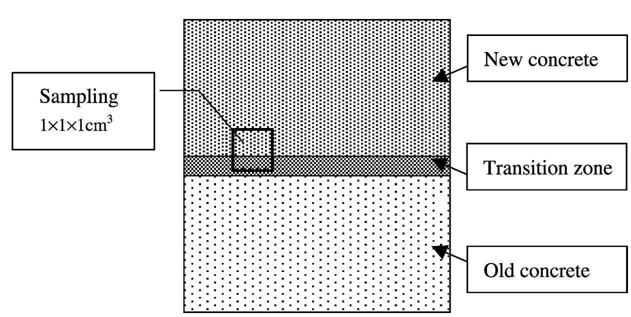

Fig. 3. Sampling for SEM/EDS tested.

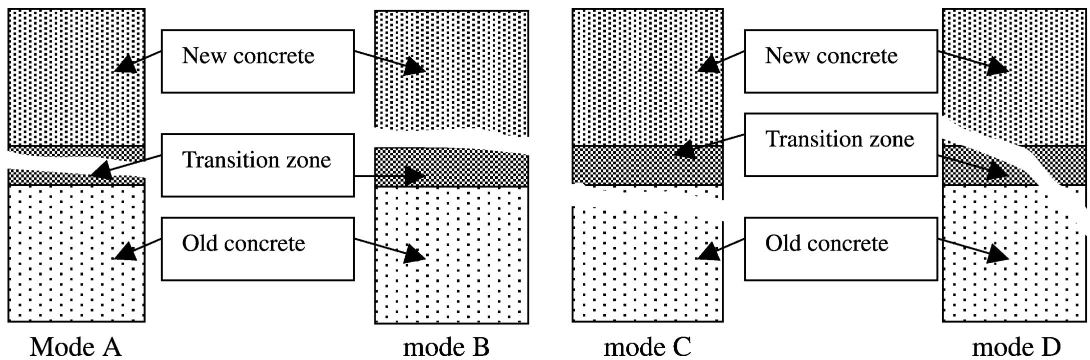

Fig. 4. Failure modes of specimens.

28 days is the lowest, but exceeds the others at the age of 1 year (Fig. 6). When the same new concrete is used, the bond strength of the specimens repaired with F-binder is higher than with other binders. The failure mode of the specimens repaired with fly ash is mainly mode B at the age of 28 days, and is mainly mode A or mode C at the age of 1 year.

The development of the split strength is speeded up in the early curing period by adding expansive agent, this is because the hydration reaction of the expansive agent is fast, and the expansive effect of the agent counteracts the drying shrinkage of cement. However, the strength decreases at the later age, because the hydration product of the expansive agent is mainly the ettringite (AFt) crystal which is mostly tabular, oriented and quite large. As can be seen from Figs. 5 and 6, when the same binder is used, the bond strength of the specimens repaired with expansive concrete at the age of 28 days is the highest, whereas at the age of 1 year is the lowest. The failure mode for this case is mainly mode A.

It can also be seen from Figs. 5 and 6 that when no binder is used, the new concretes have little influence on the bond strength of specimens. The same phenomenon exists after 1 year curing when E-binder is used. The reason is that the failures of these specimens occur mainly at the interface between new concrete and old concrete (failure mode A), as can be seen from Table 5.

4.2. Pull-off strength

Fig. 7 shows the pull-off strength development of the specimens repaired with three different new concretes and F-binder. It is indicated that the bond strength of PFC and PFF concretes continues to increase with time. Though the PFF concrete possesses the lowest strength in early ages, it has a satisfactory strength increase rate. The bond strength of PFF concrete ranges from 2.46 MPa at 28 days to 4.23 MPa at 3 years and that of PFC concrete ranges from 2.89 MPa at 28 days to 3.84 MPa at 3 years. The bond strength of PFE increases with time in the first year, reaching the highest point of 3.92 MPa, then decreases with time to 3.68 MPa after 3 years. As can be seen in Fig. 6, except the case of PFF, the bond strengths are little influenced by new concretes at 7 days of curing time. This is because the failure of these specimens occurred mainly at the interface between new concrete and old concrete (failure mode A) (Table 6).

Fig. 8 shows the pull-off strength development at the ages up to 3 years when PEF, PEE and PEC concretes and E-binder are used. At 7 days, the PEE has the highest strength, 2.375 MPa, and the PEF has the lowest strength, 2.011 MPa. The failure modes of PEF and PEC are mainly mode B before 120 days and that of PEE is mode D. Even though the PEF has the lowest strength among all concretes up to 120 days, its 1-year strength is the highest. On the contrary, the PEE has the highest bond strength at ages up to 120 days, but at the age of 1

Table 5
Failure modes of specimens for split strength tests

Binders	New concretes					
	Portland cement concrete		Expansive concrete		Fly ash concrete	
	28 days	1 year	28 days	1 year	28 days	1 year
Without binder	A	A	A	A	A	A
C-binder	A	A	A	A	B	A
E-binder	B	A	D	A	B	A
F-binder	A	B	A	B	B	C

Table 6
Failure modes of specimens for pull-off strength tests

Mix codes	7 days	28 days	120 days	1 year	3 years
PFF	A	B	D	C	C
PFE	A	D	D	B	B
PFC	A	D	D	B	C
PEF	B	B	B	A	A
PEE	D	D	D	D	A/B
PEC	B	B	B	D	A

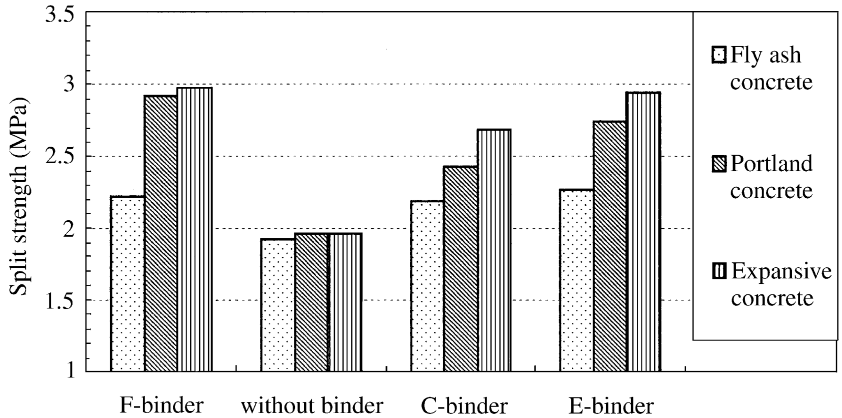

Fig. 5. Effects of the binders and new concretes on the bond strength at the age of 28 days.

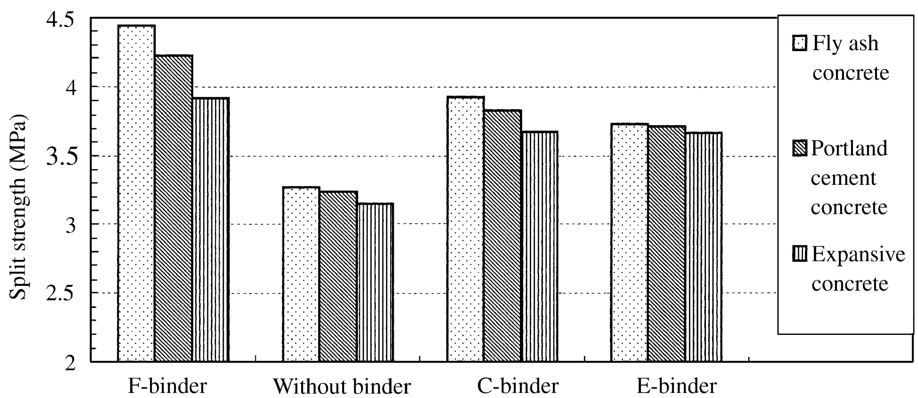

Fig. 6. Effects of the binders and new concretes on the bond strength at the age of 1 year.

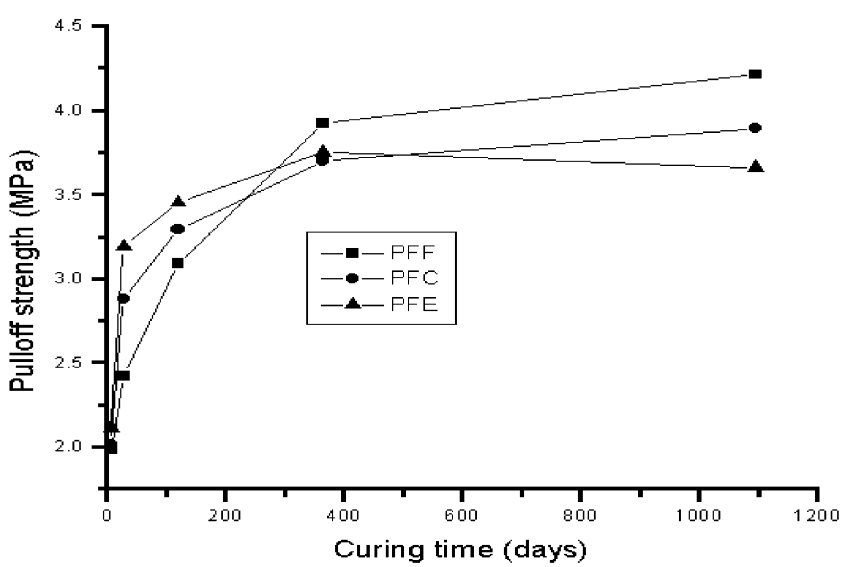

Fig. 7. Influence of new concretes on the development of pull-off strength when F-binder is used.

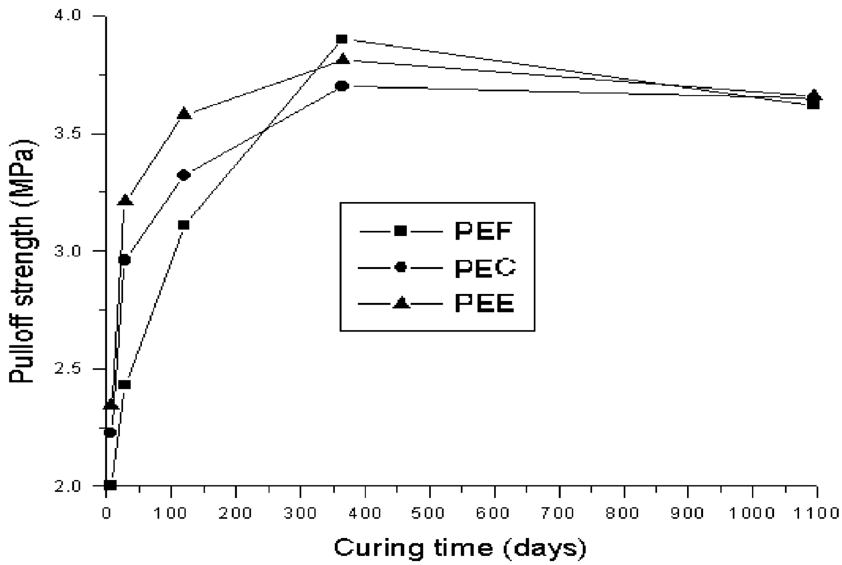

Fig. 8. Influence of new concretes on the development of pull-off strength when E-binder is used.

year its strength is lower than that of PEF. All specimens with different new concretes possess the same strength at the age of 3 years and their failure modes are mainly mode A.

5. Results of the microanalysis

As shown in Fig. 9, for PFF concrete, the interface is composed of dense C–S–H and there is no air void or

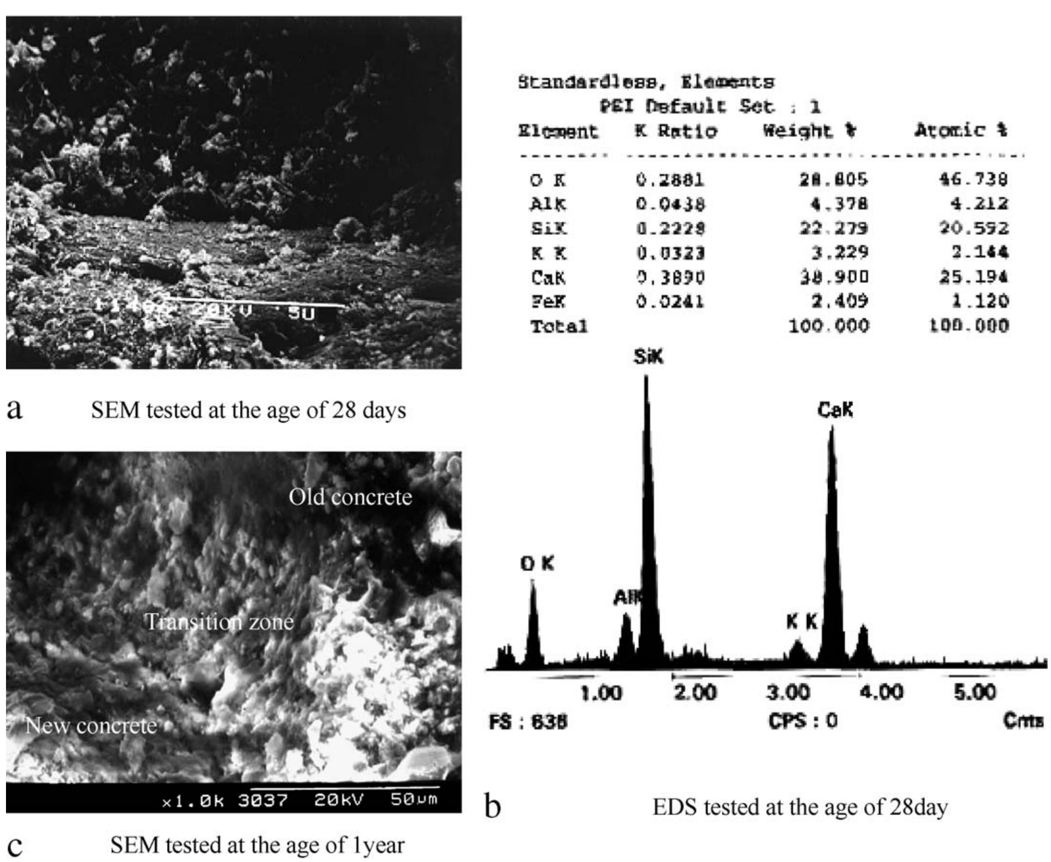

Fig. 9. Typical SEM/EDS tested results of PFF. (a, b) At the age of 28 days; (c) at the age of 1 year.

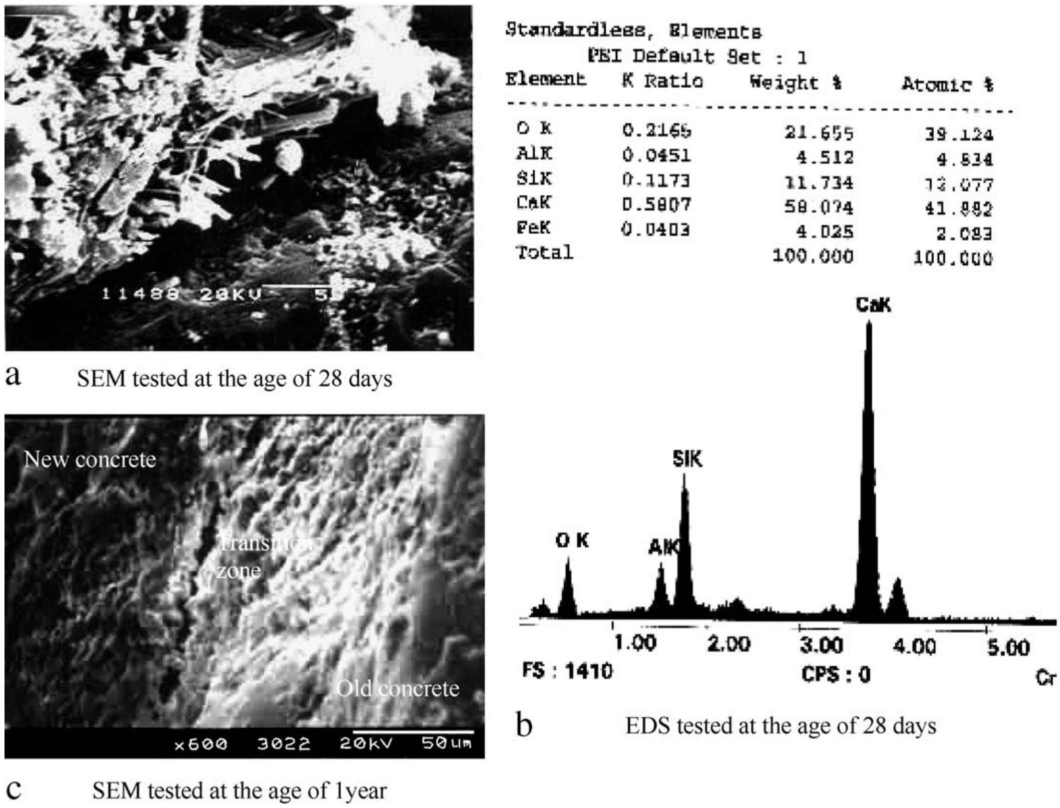

Fig. 10. Typical SEM/EDS tested results of PFC. (a, b) At the age of 28 days; (c) at the age of 1 year.

other vacant space in this region. CH, monosulfate (AFm) and AFt are not identified in the interface. An EDX spectrum at the interface (Fig. 9b) shows that Ca/Si ratio is the lowest.

For PFC concrete (Fig. 10), the interface is composed of CH (Fig. 10a). The calcium silicate hydrate (C–S–H) is much less dense and debond occurs in the interface due to cement shrinkage upon drying (Fig. 10a,c). The EDX spectrum given in Fig. 10b confirms that there exist abundant CH crystals in the interface.

The feature of PFE concrete can be seen from Fig. 11. It is shown that both CH and AFt are formed at the new-to-old concrete interface. The distribution of AFt and CH crystals is mostly tabular, oriented, quite large and space filling, as seen in Fig. 11a. The EDX spectrum at the interface shows a considerably higher Al and Ca peak, which confirms abundant AFt and CH crystals in this region (Fig. 11b). The interface zone in PFE concrete is characterized by a strong link (Fig. 11a,c).

6. Conclusions

The short-term and long-term bond strengths of new-to-old concrete were experimentally investigated with an emphasis on the influence of various new concretes and binders. The fracture properties and the microstructure of the interfacial transition zone were also studied. The following conclusions can be drawn:

1. The strength development is slowed in the early curing period by adding fly ash. However, the long-term strength is remarkably enhanced.
2. Replacement of cement constituents with expansive agent can improve the short-term bond strength. But, the long-term bond strength may decrease.
3. In bond strength tests, failures may occur in four different modes. When the binder is effective in improving the bond strength, the failure mode of specimens is mainly mode A. When the new concrete is effective in improving the bond strength, the failure mode is mainly mode B. When both the binder and the new concrete are effective in improving the bond strength, the failure mode is mainly mode C or D.
4. Fly ash can improve the microstructure of the interface. In PFF concrete, the interface zone is composed of dense C–S–H. There is no air voids or other vacant spaces in this region. CH, AFm and AFt are not identified at the interface.
5. In PFC concrete, abundant CH crystals are observed at the interface. Apart from CH, some AFt crystals are also identified in this region and debond occurs due to cement shrinkage upon drying.

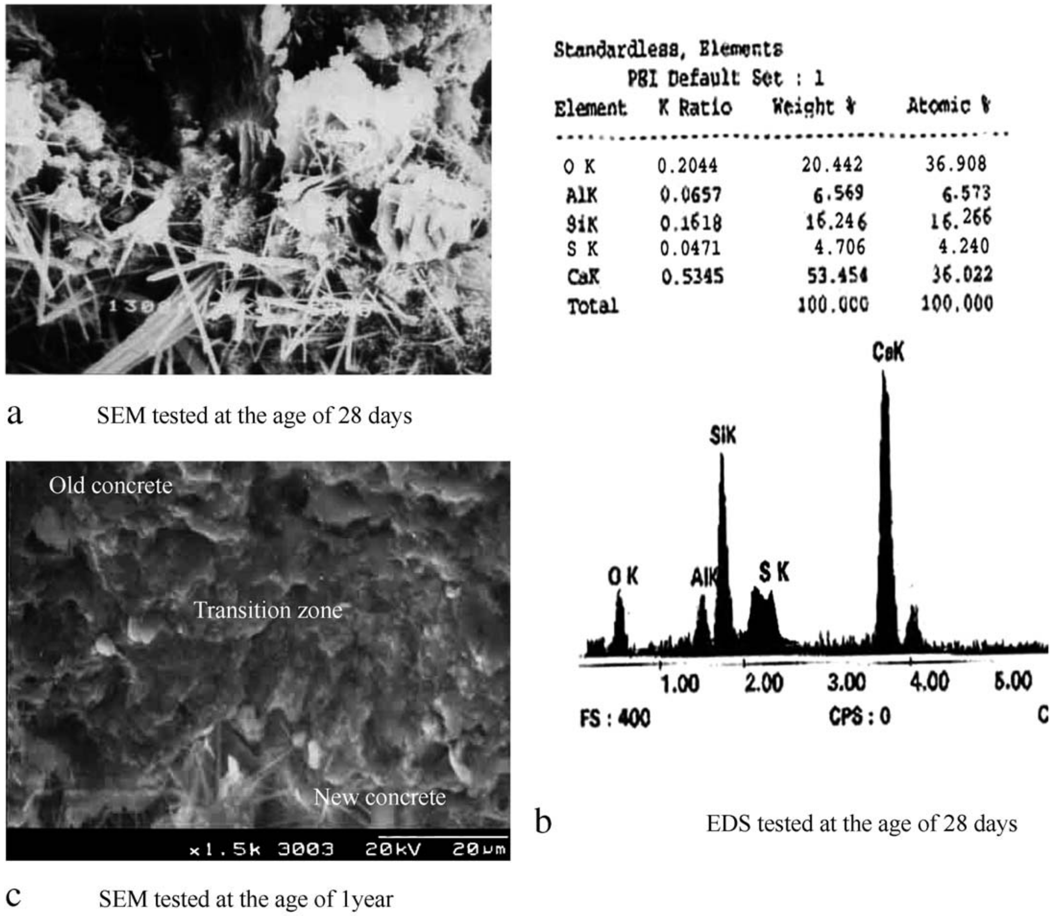

Fig. 11. Typical SEM/EDS tested results of PFE. (a, b) At the age of 28 days; (c) at the age of 1 year.

6. In PFE concrete, abundant AFt crystals and abundant CH crystals are observed at the interface. The bond is strong due to the presence of expansive agent in new concrete, which restricts the drying shrinkage of cement.

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