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Transition zone studies of new-to-old concrete with different binders

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Abstract

The weak transition zone between new and old concrete controls many properties of repaired concrete. The transition zone between aggregates and cement pastes of normal concrete has been studied by a number of researchers. But to date, there is little information available about the interfacial zone between new and old concrete. In this paper, major properties of the transition zone between new and old concrete with different binders were studied by using both scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). The bond strength was also investigated. The test results show that the binder is a vital factor, which affects the morphology (size and shape), mineralogy and the microstructure of the transition zone in repaired concrete. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Transition zone; Binder; Bond strength; Microstructure; SEM; EDS

1. Introduction

The aggregate–cement paste interface in concrete was firstly studied by Jacques Farran [1] in 1956, who observed a weak transition zone exhibiting a different mineralogy and microstructure which existed in the interface between aggregate and cement paste. It has been investigated since then by a number of researchers [2]. It was found that the zone controls many important properties of concrete [3]. It has also been indicated that the interface between the new and old concrete is the weakest link in the repaired concrete. However, there is little information about its mineralogy and microstructure.

The binder is a main factor affecting the mechanical properties and durability of repaired concrete, which is cited in Refs. [4–7]. In this paper, scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were used to observe the morphology (size and shape), mineralogy and microstructure of the transition zone in repaired concrete with different binders, including pure cement paste (C-binder), expansive binder (E-binder), polymer modified binder (YJ-302) and fly ash mortar (F-binder). The split testing was carried out to evaluate the bond strength of the interface between new and old concrete.

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2. Experimental

2.1. Materials

The cement used in the new and old concretes as well as binders was ordinary Portland cement. A Class II (Chinese Standard) fly ash from Shantou Huaneng Power Plant was selected for this work. The chemical analysis 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 the U-type expansive agent was calcium sulfoaluminate. The main composition of polymer modified binder (YJ-302) was emulsified epoxy resin. The mix proportions of binders are presented in Table 2. The composition of new and old concrete mixes was 0.46:1:1.56:2.55 (water:ordinary Portland cement:sand:stone).

2.2. Samples and tests

Split strength tests of old concrete were carried out on three-month old cube specimens ($100 \times 100 \times 100$ mm^3), according to Chinese Standard GB-8185, and the average strength of six specimens was used as an index. The split old concrete pieces (about $100 \times 100 \times 50$ mm^3)

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Table 1
Chemical and physical properties of cement (for both concretes and binders) 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	52.5	19.1	8.2	14.7	1.98	0.35	0.48	3.6	565	–

Table 2
Mix proportions of binders

Binder type	Cement	Water	Sand	Fly ash	U-type expansive agent	Super plasticizer dosage[a]
C-binder	1	0.4	–	–	–	0.5
F-binder	0.75	0.4	1	0.25	–	1.5
E-binder	0.9	0.4	–	–	0.1	0.5
Polymer (YJ-302)	One of the main components of the polymer modified binder (YJ-302) was emulsified epoxy resin					

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

were immersed in water for saturation. Afterwards the old concrete pieces were placed in plastic mold ($100 \times 100 \times 100$ mm^3), and binders were brushed on the split surface of old concrete with a thickness of 2–3 mm. Then the new concrete with the same mix proportions as the old concrete was cast. A vibrating table was used to insure good compaction. The surface of the new concrete was smoothed, and a wet cloth was covered on the concrete until demolding after 1 day. These specimens were then cured in water at room temperature, and dried 24 h prior to be tested after 28 days curing. The bond strength of these samples was determined by split method (Fig. 1), and the average strength of three specimens was used as an index.

Scanning electron microscope (SEM) analysis: six samples roughly with a size of $1 \times 1 \times 1$ cm^3 were taken from each kind of repaired concrete. Three samples were sliced from the vertical section (including new concrete, interface, and old concrete), as shown in Fig. 2. The other three samples were taken from the across-section zone near the old concrete, as shown in Fig. 3. Immediately after sampling all the samples were put into absolute alcohol. The transition zone and the across-section of the interface were observed under the H-1030 SEM with an EDS analyzer. The samples were gold-coated before examination in the SEM.

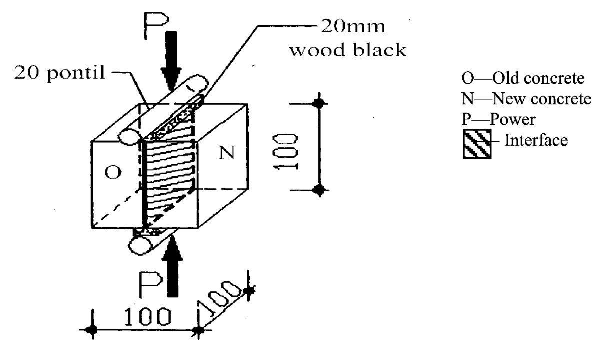

Fig. 1. Specimen for bond strength tests.

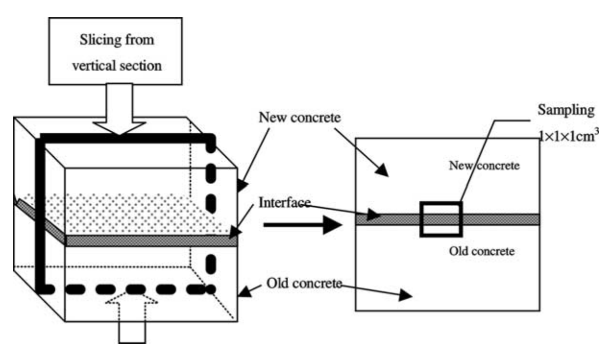

Fig. 2. Sampling from the vertical section for SEM observes.

3. Results of the microanalysis

The main results of this study are micrographs of new-to-old concrete interface (Figs. 4–11) and EDS spot analysis (Figs. 12–14).

There should be two interfaces among the new concrete, the binder, and the old concrete in theoretical sense: one is between old concrete and binder, the other is between binder and new concrete. However, only one interface (between old concrete and binder) was

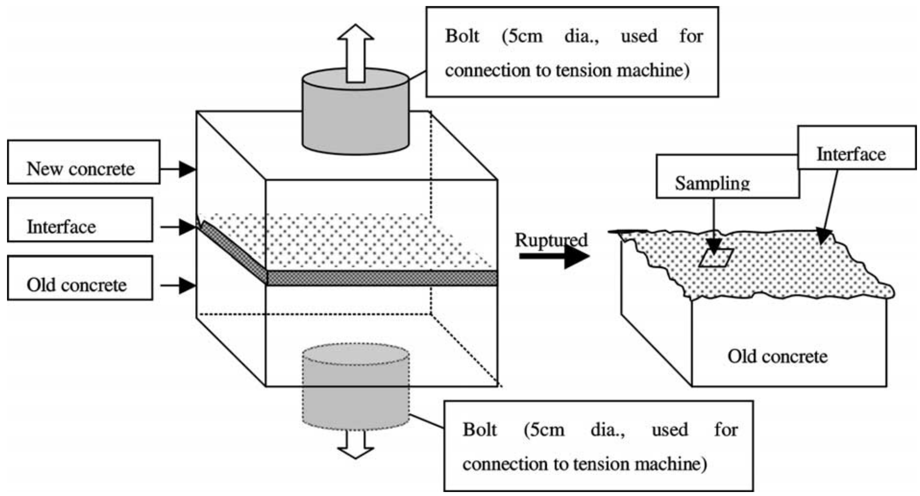

Fig. 3. Sampling from the across-section for SEM observes.

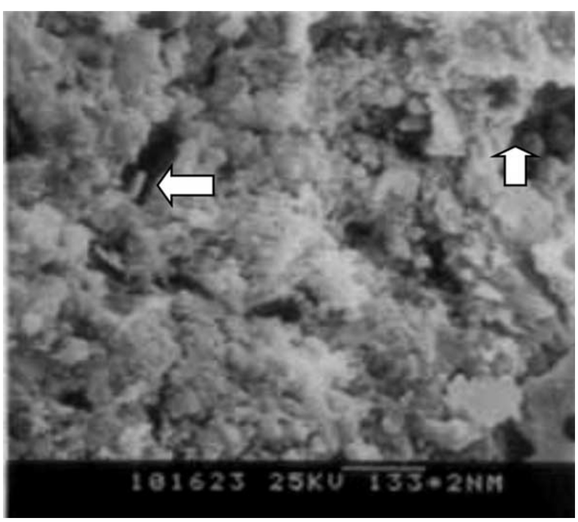

Fig. 4. SEM. The old concrete.

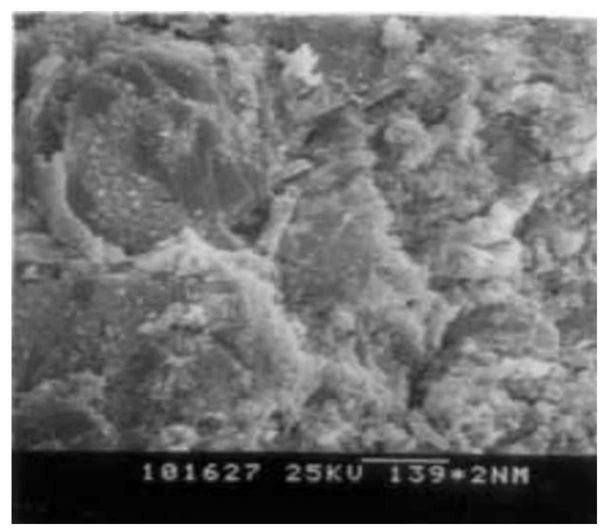

Fig. 6. SEM. The transition zone with F-binder.

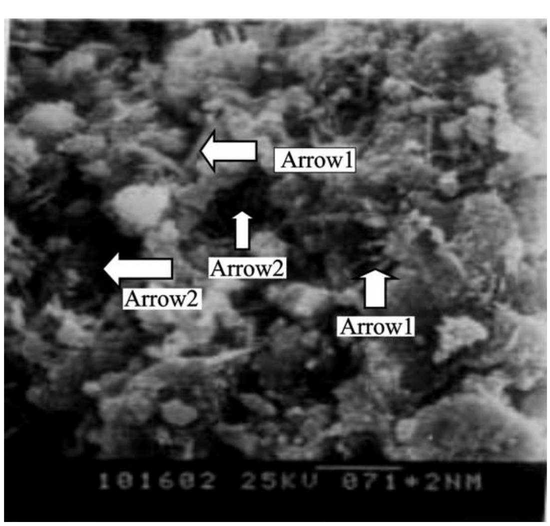

Fig. 5. SEM. The new concrete.

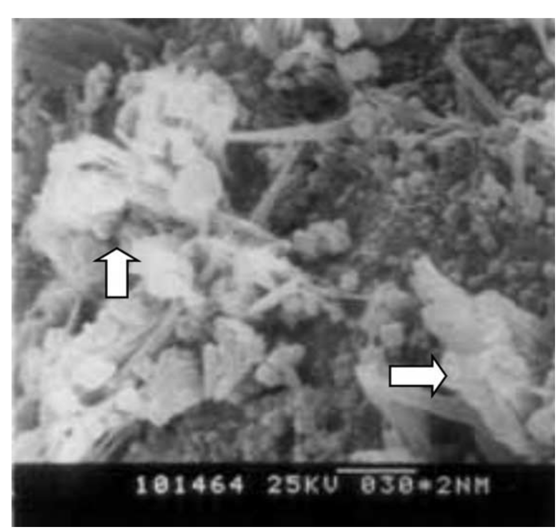

Fig. 7. SEM. The across-section of interface with F-binder.

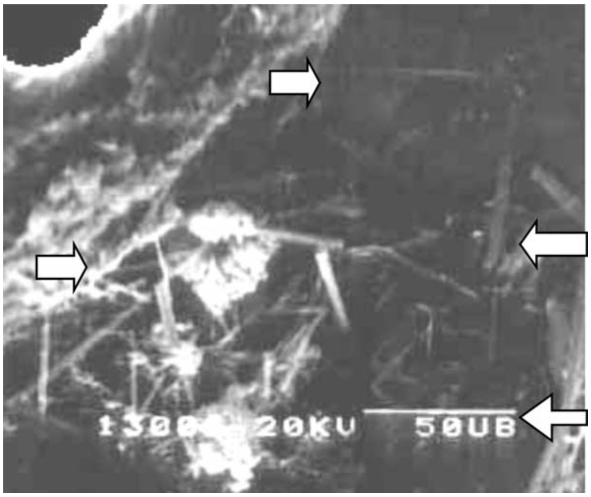

Fig. 8. SEM. The transition zone with E-binder.

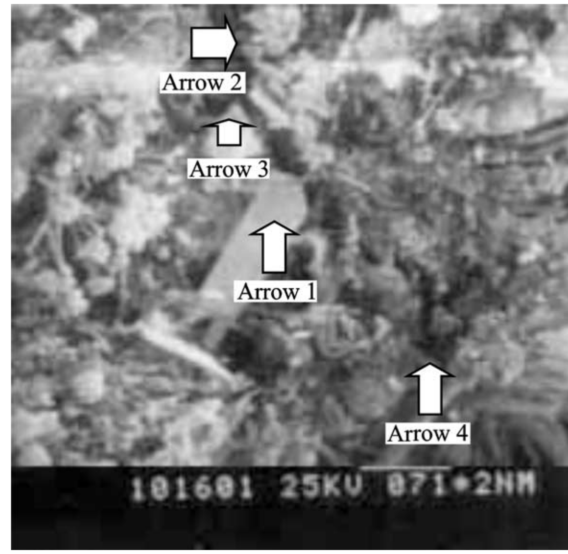

Fig. 10. SEM. The transition zone with C-binder.

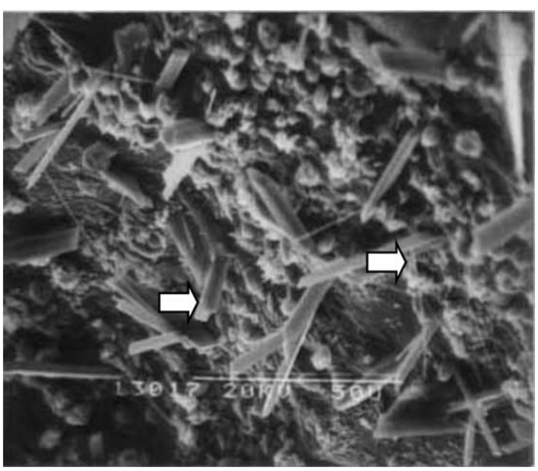

Fig. 9. SEM. The across-section of interface with E-binder.

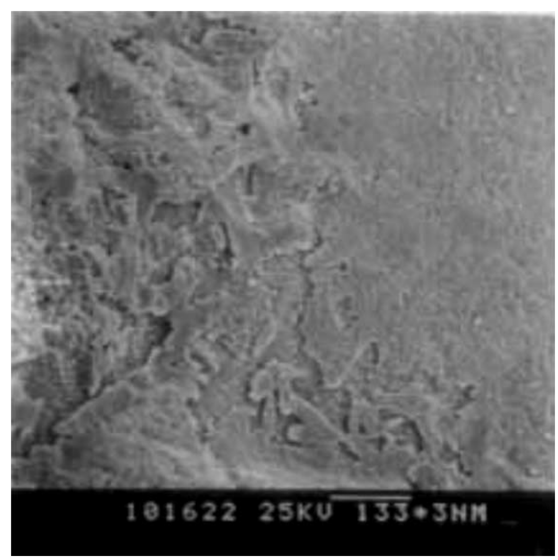

Fig. 11. SEM. The across-section of interface with polymer binder.

observed by using SEM in this study. This might be due to the fact that the new concrete and the binder mixed together during vibration on the vibrating table.

3.1. The transition zone with F-binder

In Fig. 6, the vertical section including the transition zone was observed. The transition zone was more dense and uniform than the new concrete (Fig. 4) and the old concrete (Fig. 5). Little ettringite or $Ca(OH)_2$ was observed in the transition zone. EDS analysis (Fig. 12) indicated a Ca/Si ratio of 2.73 in the transition zone.

Fig. 7 shows the morphology (size and shape) of mineralogical phase at the across-section near old concrete. C–S–H was present in large amounts, no ettringite or $Ca(OH)_2$ was observed.

3.2. The transition zone with E-binder

In Fig. 8, the vertical section including the transition zone was observed. The transition zone was porous and rich in ettringite, but poor in calcium silicate hydrates. This is because that the U-type expansive agent in the E-binder reacts with the mixing water to form ettringite. Fig. 13 shows the EDS analysis with a Ca/Si ratio of 5.36 and with an evidence of Al^{3+} ($Al^{3+} = 4.72$), which was higher than that with F-binder.

Fig. 9 shows that there is a great deal of direction distribution (perpendicular to the surface of old concrete) columned ettringite in the interface.

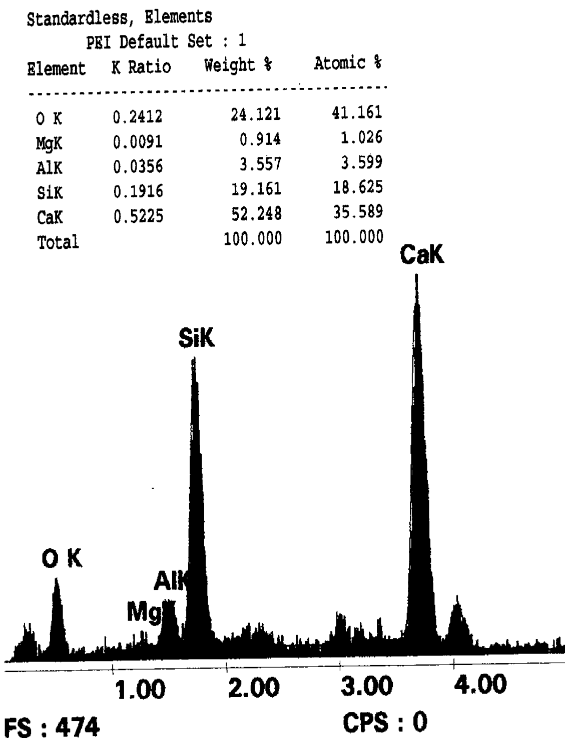

Fig. 12. EDX analysis in transition zone with F-agent.

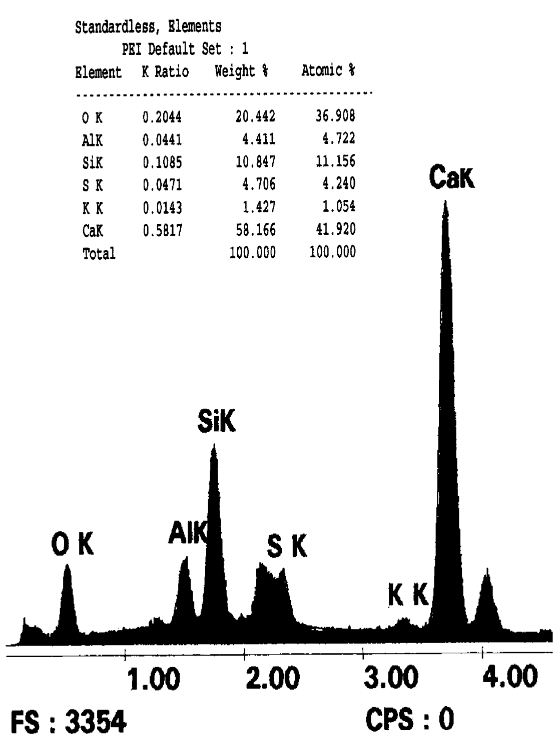

Fig. 13. EDX analysis in transition zone with E-agent.

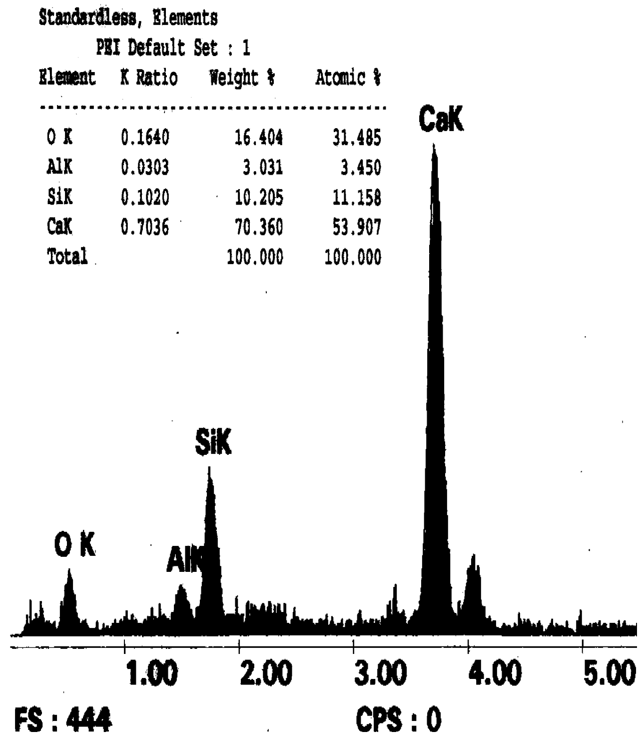

Fig. 14. EDX analysis in transition zone with C-agent.

3.3. The transition zone with C-binder

The mineralogical phase with C-binder is shown in Fig. 10. The interface included a great mount of preferentially oriented $Ca(OH)_2$ and ettringite. Debonding of the interface (arrow 2) occurs due to cement drying shrinkage. This kind of debonding was common in repaired concrete with C-binder, and was detrimental to repair. There was a plate-like crystal with a dimension greater than 150 nm (arrow 1) in the transition zone, and the transition zone was porous. EDS analysis indicated a Ca/Si ratio of 6.89, which was higher than that with E-binder, as could be seen in Fig. 14.

3.4. The transition zone with polymer modified binder

In Fig. 11, the across-section of interface near the old concrete was shown. Hydration products were hardly found, and only a polymer film in the surface was observed.

4. Main results of mechanical tests

Table 3 presents the split strength (tensile strength) of the interface between new and old concrete. To analyze the bond strength in greater details, the ratio of the bond

Table 3
Effects of the binders on the bond strength between new and old concrete

Binder	Surface disposed	Bond strength[a] (MPa)	Split strength of old concrete (MPa)	R_b/R_0[b] (%)
Unused	Natural ruptured[c]	2.05	5.38	38.1
Polymer(YJ-302)	Natural ruptured	2.09	5.34	39.0
C-binder	Natural ruptured	2.17	5.41	40.1
E-binder	Natural ruptured	2.39	5.32	45.0
F-binder	Natural ruptured	3.21	5.03	63.8

[a] Bond strength (i.e., the split strength of the interface).
[b] R_b/R_o (i.e., Bond strength/split strength of old concrete) ratio.
[c] Natural ruptured (i.e., the split surface of the old concrete).

strength to the old concrete strength is used. It can be seen that the bond strength is significantly affected by the binders. The bond strength is the highest when F-binder is used, and the lowest when polymer binder is used.

5. Discussion

The transition zone of new-to-old concrete is usually porous and rich in large crystals. This is because concrete is a hydrophilic material, which leads to a wall effect and produces a strong flow of water in the direction of the old concrete, and then induces a local increase of the water–cement ratio.

No calcium hydroxide or ettringite was observed from SEM in the transition zone when F-binder was used. The transition zone was extraordinarily dense and uniform, and the bond strength was the highest. This is because:

1. Chemically, the amorphous silica of fly ash in F-binder reacts with the calcium hydroxide produced by the hydration of cement, forming calcium silicate hydrate (C–S–H). The formation of additional C–S–H fills the pores and the pozzolanic reaction decreases the calcium hydroxide (large crystal) content.
2. Physically, the numerous fly ash globular particles in F-binder fill the weak spaces of the transition zone, which makes the transition zone extraordinarily dense and uniform.
3. Sand in F-binder restricts the drying shrinkage in the interface, and makes the link between new and old concrete quite strong.

A large number of ettringite crystals were observed in the transition zone when E-binder was used. This is due to the fact that the hydration product of the U-type expansive agent in the E-binder is mainly the ettringite crystal. EDS analysis confirmed that the content of Al^{3+} of transition zone (Fig. 13) is the highest. The large crystals induce many micro-cracks in the transition zone. The bond strength is lower than that with F-binder, although the expansive effect of U-type expansive agent counteracts the dry shrinkage of cement.

The bond strength was low when C-binder was used, because there were a large number of macro-cracks and large crystals (Fig. 10) in the transition zone, and the new-to-old concrete interface debonded due to the cement drying shrinkage.

The bond strength is the lowest when polymer modified (YJ-302) binder is used, because the bond of new-to-old concrete depends mainly on glutinous nature of polymer (molecular force) [7]. Crystals in the interface were not found (Fig. 11).

6. Conclusions

1. The transition zone was compact, and no calcium hydroxide or ettringite was observed from SEM, when F-binder was used. The Ca/Si ratio was the lowest, and the bond strength was the highest.
2. The transition zone was rich in cracks and ettringite crystals when E-binder was used. The Ca/Si ratio was higher, and the bond strength was lower than that with F-binder.
3. When C-binder was used, the transition zone was porous, rich in $Ca(OH)_2$ and ettringite crystals. Debonding occurs in the interface due to cement drying shrinkage. The Ca/Si ratio was higher, and the bond strength was lower than that with E-binder.
4. A polymer film was formed when polymer binder (FJ-302) was used, and the bond strength was the lowest.

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