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Improve the strength of concrete-filled steel tubular columns by the use of fly ash

Gengying Li*, Xiaohua Zhao, Liqiang Chen

Department of Civil Engineering, Shantou University, Shantou 515063, China

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Abstract

Concrete-filled steel tubular columns (CFTs) are becoming widely used in engineering. In the present paper, the addition of fly ash and an expansive agent to the concrete of CFTs or a thin layer of fly ash to the interface between steel tube and concrete (CFTFCs) to improve the compressive strength and the bond strength of CFTs was experimentally investigated. The results show that the expansive concrete-filled steel tubular columns (CFETs) have the highest bond strength and compressive strength at the age of 7 days, and CFTFCs have higher bond strength and compressive strength than fly ash concrete-filled steel tubular columns (CFFTs), which in turn are higher than CFTs. However, both bond strength and compressive strength of CFTFCs become the highest at the age of 28 days. The morphology (size and shape) of mineralogy and microstructure of the interface at the age of 28 days were also investigated by using both scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). It is shown that the strength improvement of CFTFCs mainly depends on the content of SiO_2 and CaO in the interface, and higher content of SiO_2 and/or lower content of CaO are preferred.

Keywords: Fly ash; Concrete-filled steel tubular column; Bond strength; Compressive strength; SEM

1. Introduction

The use of concrete-filled steel tubular columns (CFTs) in high-rise buildings has become popular in recent years as they provide several advantages over reinforced concrete or steel columns [1–5]. Though researches into the behavior of CFTs have been carried out for many years since the first test on encased steel sections conducted by Burr in 1908 [6], little progress was made until the latter half of the twentieth century. Presently, a better understanding of CFTs' behavior has been established by a number of investigations. Those include the works of Virdi and Dowling and Tomii et al. [7] on bond strength, Minami et al. [8] and Suzuki and Kato on shear capacity, and Zandonini [9] on semirigid composite joints. Time effects have been addressed by Bradford and Gilbert [10,11] and Rangan [12]. However, information is still unavailable about the behavior of the interface between concrete and steel tube.

It is well known that the transition zone forms at the paste side between paste and aggregate or steel bar [13], as well as between new and old concrete [14]. Many investigations have focused on the transition zone between normal aggregate and paste. It is shown that the transition zone possesses a more porous structure than the bulk paste, and its thickness varies from 20 to 100 μm, depending on the characteristics of the surface in contact with fresh paste, water/cement ratio, chemical compositions and so on. Moreover, the formation of relatively large hexagonal calcium hydrate crystals and their orientation were considered the most important factors affecting the behavior of the zone [15–18].

Since the durability, permeability and strength of concrete are significantly influenced by the behavior of the transition zone, modifying its microstructure has been one of great concerns. Replacement of cement constituents with several pozzolanic materials, addition of some organic polymers and reduction of thickness of water film by adding detergents have been investigated as modification methods [19–21]. It is reported that the use of silica fume and fly ash is effective in improving the structure of the transition zone because of a microfiller effect of the materials or their prevention of the growth of calcium hydrate crystals [22–24]. Studies also

* Corresponding author. Tel.: +86-754-8367-533; fax: +86-754-2902-510.

E-mail address: gyli@stu.edu.cn (G. Li).

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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-day 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	–

show that the use of an expansive agent is effective in improving the transition zone of new-to-old concrete [14].

The interface between steel tube and concrete has a similar structure as the transition zone of normal aggregate and paste. In this work, its effect on the strength of CFTs is considered. The addition of fly ash and an expansive agent to the concrete of CFTs or a thin layer of fly ash to the interface to improve the compressive strength and the bond strength of CFTs was experimentally investigated. The microstructure of the interface at the age of 28 days was also studied by using both scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS).

2. Methods

2.1. Materials

The cement used in the mixes was ordinary Portland cement. Fly ash of Class II (Chinese Standard) from Huaneng Power Plant of Shantou was selected for this work. Their chemical analysis and physical properties 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. A U-type expansive agent from Tianjing in China was used in the work, and its chemical analysis and physical properties are presented in Table 2. The mix proportions of concrete are presented in Table 3.

The steel tube used in the study was Q235, with a diameter of 100 mm, a height of 300 mm and a thickness of 16 mm. Its compressive strength was 499.2 MPa.

2.2. Testing procedures

Six specimens for each mix were prepared for the testing of compressive strength. All empty steel tubes were accurately machined to the desired length with a lathe and both ends of them were smoothed. Then, the bottom of the tubes was welded with a steel cap plate (Fig. 1). Before casting concrete, the tubes were thoroughly degreased and rinsed with hot water. Once dried, for CFTs, fly ash (CFFTs) and expansive concrete-filled steel tubular columns (CFETs), plastic concrete was placed in layers in the vertical tubes and compacted using a vibrator. For CFTFCs, the inner surface of each tube was coated with a thin layer of fly ash prior to casting, which was done with a porous cloth by hand. When finished, a steel cap plate was used to seal the top of each column.

To determine the bond strength, a direct tensile testing was conducted on six specimens for each mix (Fig. 2). The schematic diagram for the testing is shown in Fig. 4. The specimens of CFTs, CFFTs and CFETs were prepared as follows: a steel bar with a cross-end (Fig. 3) was firstly inserted into the steel tube along its central axis, which would be mounted to a special device of the testing machine, and then plastic concrete was filled. For CFTFCs, before inserting steel bar, the inner surface of each steel tube was coated with a thin layer of fly ash. Finally, the specimens were compacted using a vibrator, and a plastic cap plate was used to seal the top of each column.

All specimens were cured in a laboratory condition. During the curing period, both the top and the bottom of each column were carefully inspected, and the voids would be filled with a high-strength epoxy if they were found. The top cap plate was taken away before testing.

SEM analysis: three samples with a size of $1 \times 1 \times 1$ cm were prepared for each mix at the age of 28 days, and they were taken from the interface between concrete and steel tube after the bond strength tested. All samples were kept in pure alcohol until test and were gold-coated before exam-

Table 2
Chemical and physical properties of expansive agent

Color and shape	Hoar power
Specific gravity (g/cm^3)	2.88
Fineness (0.08 mm, %)	5.19
Specific surface (cm^2/g)	3500
Expansive rate (14 days in water, %)	0.02–0.04
Self-stress (dosage 8–14%, MPa)	0.2–0.8
Causticity to steel tube	No

Table 3
Different types of mixture proportions used

Mixture type	Concrete of CFTs	Concrete of CFFTs	Concrete of CFETs	Concrete of CFTFCs
Cement, C (kg/m^3)	411	370	370	411
Fly ash (kg/m^3)		41		
Expansive agent (kg/m^3)			41	
Sand (kg/m^3)	629	620	629	629
Coarse aggregate (kg/m^3)	1221	1216	1221	1221
Water (kg/m^3)	152	152	152	152
Superplasticizer (kg/m^3)	4.11	4.93	3.7	4.11
W/B *	0.38	0.38	0.38	0.38
Slump (mm)	45	45	45	45

W/B* give as total.

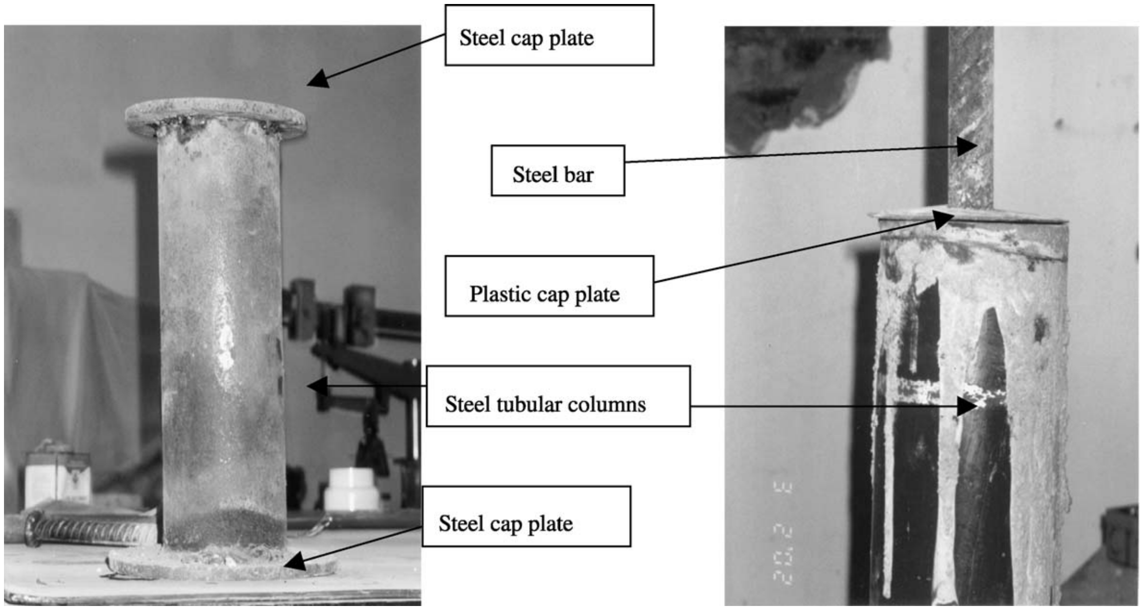

Fig. 1. Specimen for testing of compressive strength.
Fig. 2. Specimen for testing of bond strength.

ination. The interface was observed under the H-1030 SEM with EDS analyzer.

3. Testing results

3.1. Bond strength

The tensile strength for the specimens is shown in Table 4. We can see from the table that at 7 days of curing time, CFETs have the highest bond strength, while the bond strength of CFFTs is the lowest, and the bond strength of CFTFCs is slightly higher than that of CFTs. At the age of 28 days, the bond strength of CFTFCs becomes the highest, while that of CFTs is the lowest, and the bond strength of CFFTs is higher than that of CFTs.

Table 4 also shows the bond strength gain of the concretes between 7 and 28 days. Though CFFTs have lower strength than CFTFCs and CFETs at the age of 28 days, their strength gain is the highest, up to 45.1% between 7 and 28 days. For CFETs, their strength gain becomes the lowest, about 27.7%.

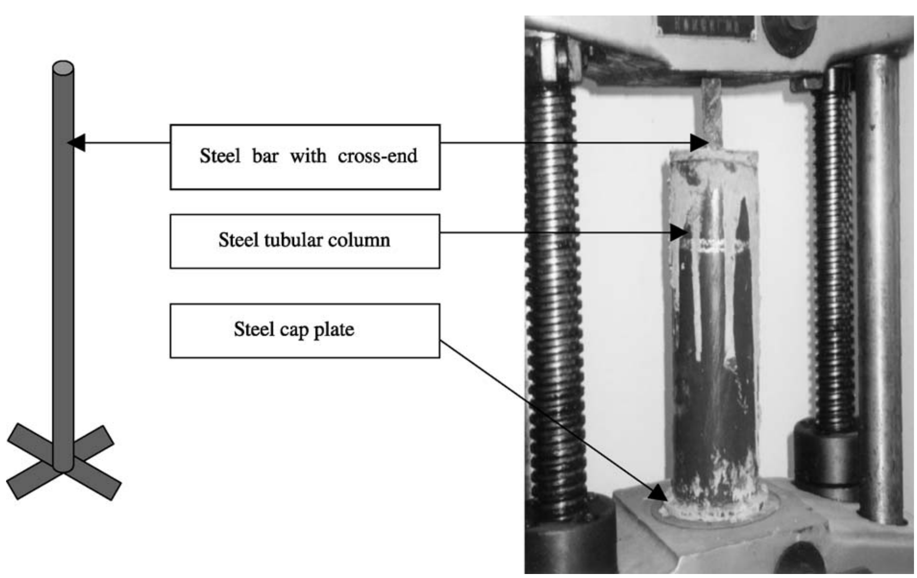

Fig. 3. Steel bar with a cross-end.
Fig. 4. Schematic diagram of the specimen for testing of bond strength.

Table 4
Test results of bond strength

No.	7-day bond strength (MPa)	28-day bond strength (MPa)	Strength gain from 7 to 28 days (%)
CFTs	5.16	6.56	28.1
CFFTs	4.88	7.08	45.1
CFETs	5.64	7.20	27.7
CFTFCs	5.24	7.56	44.3

3.2. Axial compressive strength

The measured strength of each mix is shown in Table 5. At the age of 7 days, the compressive strength of CFETs is the highest and that of CFTFs is higher than that of CFTs, which in turn is slightly higher than that of CFFTs. However, the strength of CFTFCs becomes the highest and that of CFTs is the lowest at the age of 28 days.

Table 5 shows the strength gain of the concretes between 7 and 28 days. Though the 28-day strength of CFFTs is lower than that of CFTFCs and CFETs, CFFTs have the highest strength gain of 30.6% between 7 and 28 days. For CFETs, though they have a higher 7-day and 28-day strength, their strength gain is the lowest, about 21.3%.

3.3. Microanalysis

The main results are micrographs of interface (Figs. 3a–6a) and EDS spot analysis (Figs. 3b–6b).

As shown in Fig. 3, the interface of CFTFCs is composed of dense C–S–H, and there are few air voids or other vacant spaces in this region. CH, monosulfate (AFm) and ettringite (Aft) are not identified. An EDX spectrum at the interface (Fig. 3b) shows that Si content is the highest, while Ca content is the lowest, which is due to the fact that the content of CaO in fly ash is lower than in cement.

The interface of CFFTs is also composed of C–S–H (Fig. 4a), and air voids or vacant spaces are more than those of CFTFCs. CH, Afm and AFt are not identified. An EDX spectrum (Fig. 4b) shows that Si content is lower and Ca content is higher than that of CFTFCs.

For CFETs (Fig. 5), AFt is formed at the interface, and its distribution is mostly tabular, oriented, quite large and space filling, as can be seen in Fig. 5a. The EDX spectrum shows a considerably higher Al and Ca peak, which confirms the existence of abundant AFt in this region.

Table 5
Test results of axial compressive strength

No.	7-day compressive strength (MPa)	28-day compressive strength (MPa)	Strength gain from 7 to 28 days (%)
CFTs	121.6	148.9	22.4
CFFTs	115.2	150.5	30.6
CFETs	126.4	153.3	21.3
CFTFCs	122.3	156.7	28.1

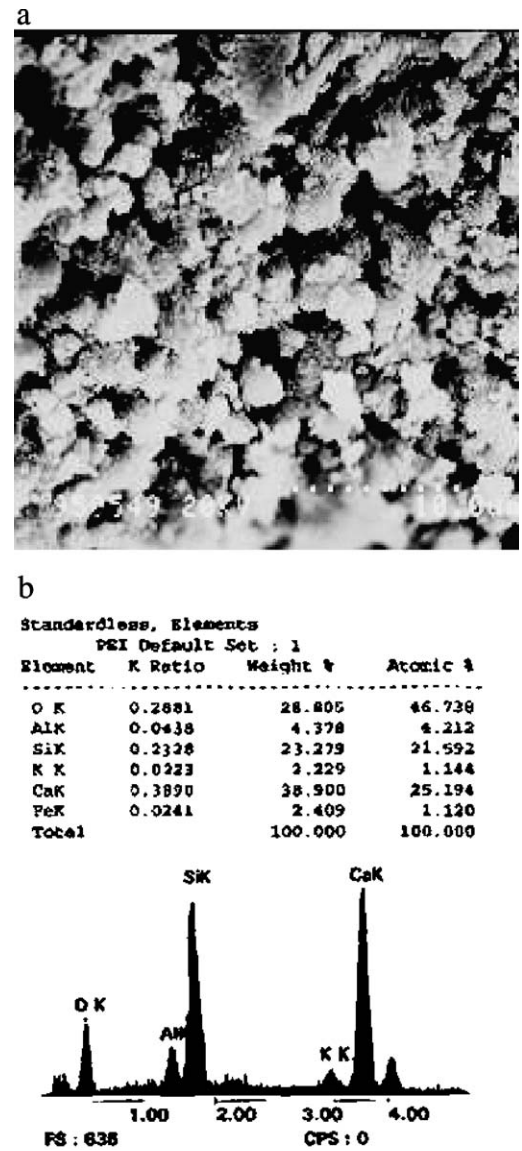

Fig. 5. Typical SEM/EDS test results of CFTFCs.

Fig. 6 shows that C–S–H is much less dense in the interface of CFFTs, and there are plenty of big air voids due to cement shrinkage upon drying (Fig. 6a). The EDX spectrum in Fig. 6b shows that Ca content is high, which confirms the abundant CH crystals in the region.

4. Discussion

From the above analysis, we can see that the interface between steel tube and concrete is porous and rich in big crystals. The reason is that the steel tube is a hydrophilic material, which may lead to the wall effect and produce a strong flow of water towards the surface of the steel tube, and then induce a local increase of the water–cement ratio. In the present case, because the specimens were tightly

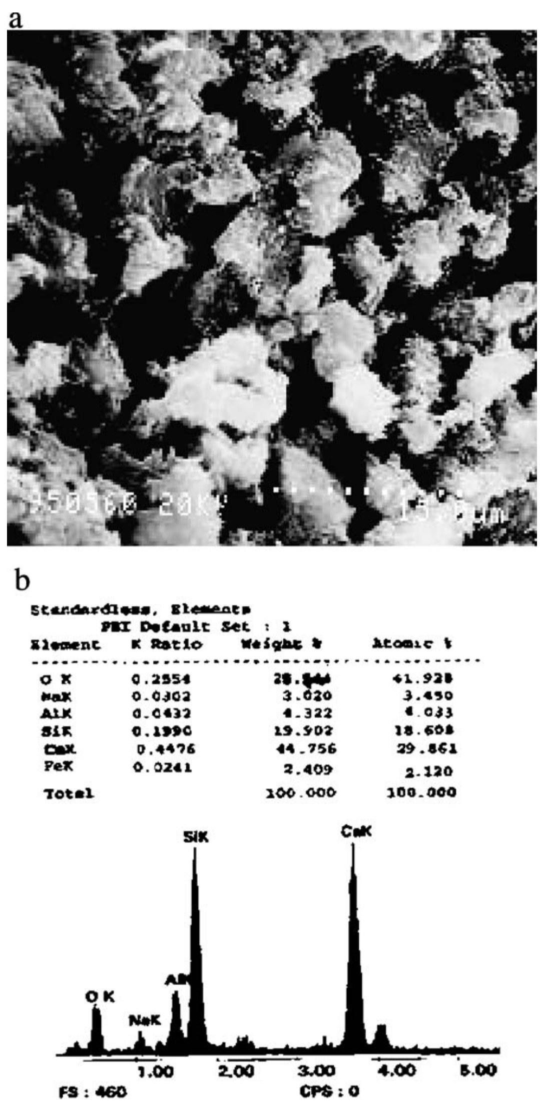

Fig. 6. Typical SEM/EDS test results of CFFTs.

sealed, the free water could not run away and congregated on the surface of the steel tube. The congregated water leaded to not only the increase of water–cement ratio, which caused the interface being more porous, as well as the hydrate crystals being large and orientated, but also the existence of voids and/or debonding between the steel tube and concrete.

When expansive concrete was used, due to the volume expansion during the hydration of the expansive agent, the concrete in CFETs became compacted. Moreover, the porosity of the interface, the number of voids and/or debonding between steel tube and concrete were reduced, which leaded to the increase of the bond strength between the steel tube and concrete. From Tables 4 and 5, it can be seen that both of the bond strength and the compressive strength of CFETs are higher than that of CFTs. However, because the reaction of the expansive agent is fast, which may finish before 7 days, the strength gain of CFETs from 7 to 28 days is the lowest (Figs. 7 and 8).

When fly ash concrete was used, the pozzloanic reaction with calcium hydroxide reduced the content of calcium hydroxide and increased the content of C–S–H in the interface and, as a result, increased the density of this layer. Because the specific surface of C–S–H was larger than that of calcium hydroxide, the bond strength increased. We can see that the bond strength of CFFTs is higher than that of CFTs at the age of 28 days (Tables 4 and 5). The increased bond strength further leaded to the increase of the compressive strength of CFFTs. At the same time, fly ash reduced the porosity of concrete because of a microfiller effect and prevented the growth of calcium hydrate crystals and, therefore, the compressive strength of the concrete in CFFTs increased. Further, the compressive strength of CFFTs increased. However, because the strength development of fly ash concrete was slow in the early curing period, both of the bond strength and the compressive strength of CFFTs were low at the age of 7 days.

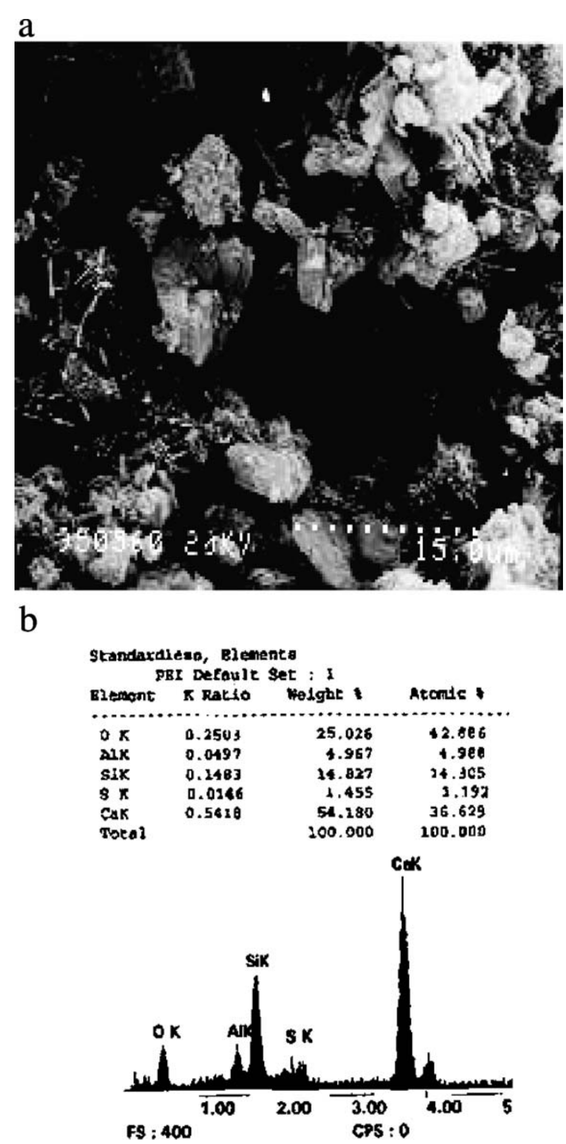

Fig. 7. Typical SEM/EDS test results of CFTs.

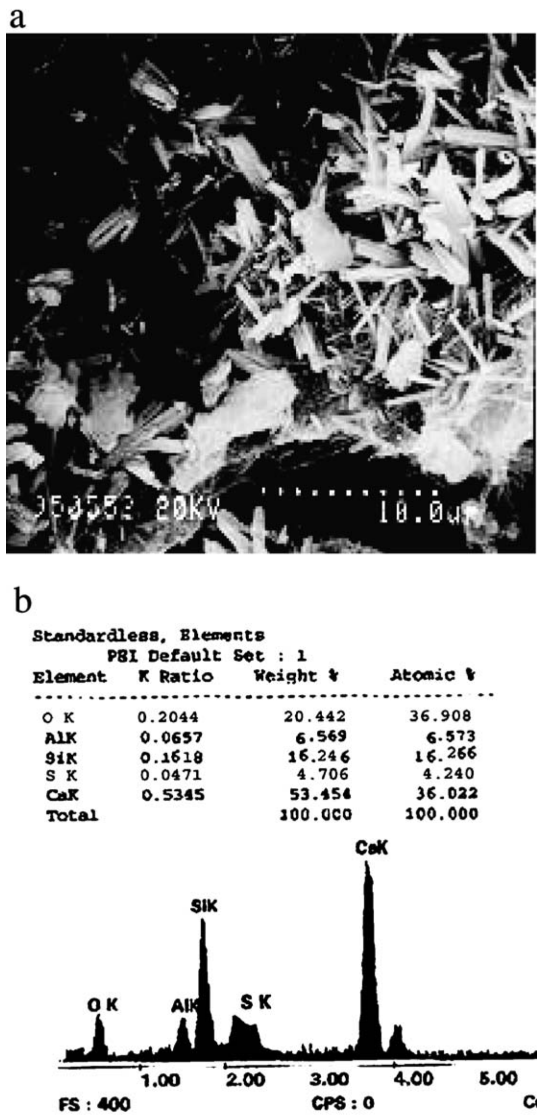

Fig. 8. Typical SEM/EDS test results of CFETs.

For the case of steel tube coated with a layer of fly ash, both of the bond strength and the compressive strength of CFTFCs increased. This may be explained from two aspects. Firstly, the pozzloanic reaction of fly ash with calcium hydroxide reduced the content of calcium hydroxide and increased the content of C–S–H in the interface, and hence increased the density of this region. Secondly, fly ash reacted with the congregated water near the surface of steel tube, which reduced the water–cement ratio and the number of voids between steel tube and concrete. Because the concrete in CFTFCs incorporated no fly ash, the rate of its strength development was the same as that of the concrete in CFTs. However, the compressive strength of CFTFCs was higher than that of CFTs at all test ages. This means that the compressive strength of CFTs is influenced by the properties of the interface between steel tube and concrete. The higher the bond strength is, the higher the compressive strength of CFTs will be.

5. Conclusions

Based on the experimental investigations of the bond strength, the compressive strength and the microstructure of the interface, the following conclusions can be drawn:

(1) The bond strength and the compressive strength of CFTs can be improved by adding a thin layer of fly ash to the interface between concrete and steel tube.
(2) The bond strength and the compressive strength of CFTs are weakened at the age of 7 days by adding fly ash into concrete, but the strengths are slightly enhanced at the age of 28 days.
(3) The bond strength and compressive strength of CFTs are remarkably enhanced at the age of 7 days by adding an expansive agent into concrete, but the strength gain from 7 days to 28 days is low.
(4) The interface of CFTFCs is composed of dense C–S–H and there are few air voids or other vacant spaces in this region. CH, Afm and AFt are not identified. Si content is the highest, but Ca content is the lowest due to the fact that the content of CaO in fly ash is lower than in cement.
(5) The interface of CFFTs is also composed of C–S–H, but air voids or vacant spaces are more than in CFTFCs, and Si content is lower than that in CFTFCs.
(6) A porous structure of C–S–H is observed at the interface of CFTs and some AFt crystals are identified.
(7) In CFETs, plenty of AFt crystals are observed at the interface, and the bond is strong due to the action of the expansive agent in concrete, which restricts the drying shrinkage of cement.

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