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# Behaviour of concrete-filled steel tubular columns incorporating fly ash

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**Abstract**

The subject of this work is to investigate the effect of fly ash on the strength of concrete filled steel tubular columns from 28 to 365 days. A contrast study was carried out on concrete filled steel tubular columns incorporating 10–40 wt% fly ash, and for control Portland cement concrete filled steel tubular columns. The effect of pre-coating the inner surface of steel tubes with a thin layer of fly ash was also studied. Assessments of the concrete mixes were based on the compressive strength and the bond strength. The results show that a lower replacement with fly ash can improve both bond strength and compressive strength, while a higher replacement with fly ash requires a relatively longer time to achieve similar beneficial effects. Pre-coating the inner surface of steel tubes with a thin layer of fly ash can notably improve the bond strength. The microstructure of the interface between concrete and steel tube was also studied by using scanning electron microscopy analyzer.


*Keywords:* Fly ash; Concrete filled steel tubular columns; Bond strength; Compressive strength; SEM

## 1. Introduction

The use of concrete-filled steel tubular (CFT) columns in high-rise buildings has become popular in recent years as they provide several advantages over reinforced concrete and steel columns, for example: (a) some construction activities become easier by eliminating formwork and reinforcement; (b) the concretes infill contributes to the stability of the steel tube and enhances strength, so smaller diameters tubes with smaller wall thicknesses can be used; (c) high strength and stiffness can be achieved by filling high-strength tubes with high-strength concrete [1–5]. A better understanding of the behavior of CFT columns has been established by a number of investigations. However, little information is available about the effect of incorporating fly ash and its replacement levels on the long-term behavior of CFT columns. It is well known that the strength of ordinary Portland cement concrete is significantly influenced by the replacement of cement with fly ash [6,7]. It is reported that the use of fly ash will reduce the early-term strength due to its low pozzolanic activity [8]. In this work, the effect of the addition of fly ash (10–40 wt%) on the strength of CFT columns up to 365 days is considered. The effect of pre-coating the inner surface of steel tubes with a thin layer of fly ash on the mechanical properties of the CFT columns was also experimentally investigated.

It is well known that a transition zone forms at the paste side between paste and aggregate or steel bar. Many investigations have shown that the transition zone possesses a more porous structure and larger hexagonal calcium hydrate crystals than the bulk paste [9,10]. It is also shown that the microstructure can be densified through the addition of pozzolans such as silica fume and fly ash. According to Bentz et al. [11,12], the presence of silica fume or fly ash produces a more homogeneous microstructure by balancing the Ca/Si molar ratio in the interfacial zone relative to that in the bulk paste, quite different from ordinary Portland cement concrete, where this ratio increases dramatically as the aggregate surface is approached. The

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interface between steel tube and concrete has a similar structure as that of normal aggregate and paste. In this paper, the effect of fly ash on the microstructure of the interface between concrete and steel tube after 1 year curing was experimentally investigated by using both scanning electron microscopy (SEM) analysis and energy dispersive spectroscopy (EDS) analyzer. The microstructure of the centre zone for both the high-volume fly ash concrete filled steel tubular columns (40 wt%) (FCTs4) and the high-volume fly ash concrete (40 wt%) (FCC4) after 365 days curing was also studied.

## 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. The mix proportions of concrete are presented in Table 2.

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

To investigate the compressive and bond strength of concrete filled steel tubular columns, twenty-four specimens for each mix were prepared for the strength test. Twelve of them were used for compressive strength tests, and the others for bond strength tests. Before casting concrete, the bottom of all empty steel tubes was welded with a steel cap plate, and the tubes were thoroughly degreased and rinsed with hot water. For compressive strength test of control Portland cement concrete filled steel tubular (PCTs) and fly ash concrete filled steel tubular columns (FCTs), plastic concrete was placed in layers in the vertical tubes and compacted using a vibrator. When finished, a steel cap plate was used to seal the top of each column. To determine the bond strength of PCTs and FCTs, a steel bar with a cross-end was firstly inserted into the steel tube along its central axis (Fig. 1), which would be mounted to a special device of the testing machine, and then the tube was filled with plastic concrete. For FFTs, before inserting the steel bar, the inner surface of each steel tube was coated with a thin layer of fly ash (about 100 μm) using a porous cloth by hand. 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 the laboratory condition. During the curing period, both the top and the bottom of each column were carefully inspected, and any voids were filled with a high-strength epoxy. The top cap plate was taken away before testing.

To investigate the compressive strength development of core concrete with different fly ash replacement levels, 12 specimens for each mix were prepared. Strength tests of core concrete were carried out on cube specimens (100 mm) according to Chinese Standard GB-8185, and the average strength of three specimens was used as an index. These specimens were covered with a wet cloth until they were demolded 1 day after casting. Then they were stored in laboratory before testing. The compressive strength of these samples was measured after curing for 28 days, 56 days, 120 days and 1 year.

The microstructure of the interface between concrete and steel tube for PCTs, FCTs4 and FFTs has been studied by using scanning electron microscope (SEM) analysis. Three samples with a size of 1 cm × 1 cm × 1 cm were

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 area ($m^2$/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 | 56.5 | 20.1 | 8.2 | 9.7 | 1.98 | 0.35 | 0.48 | 3.6 | 565 | – |

Table 2
Mixture proportions used (kg/$m^3$)

| Mixture type | Concrete of PCTs/PCC | Concrete of FCTs1/FCC1 | Concrete of FCTs2/FCC2 | Concrete of FCTs4/FCC4 | Concrete of FFTs |
|---|---|---|---|---|---|
| Cement (C) | 411 | 370 | 329 | 245 | 411 |
| Fly ash | | 41 | 84 | 168 | |
| Sand | 629 | 626 | 620 | 613 | 629 |
| Coarse aggregate | 1221 | 1216 | 1209 | 1118 | 1221 |
| Water | 152 | 152 | 152 | 152 | 152 |
| Superplasticizer | 4.11 | 3.45 | 3.1 | 2.6 | 4.11 |
| W/B | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 |
| Slump, mm | 45 | 45 | 45 | 45 | 45 |

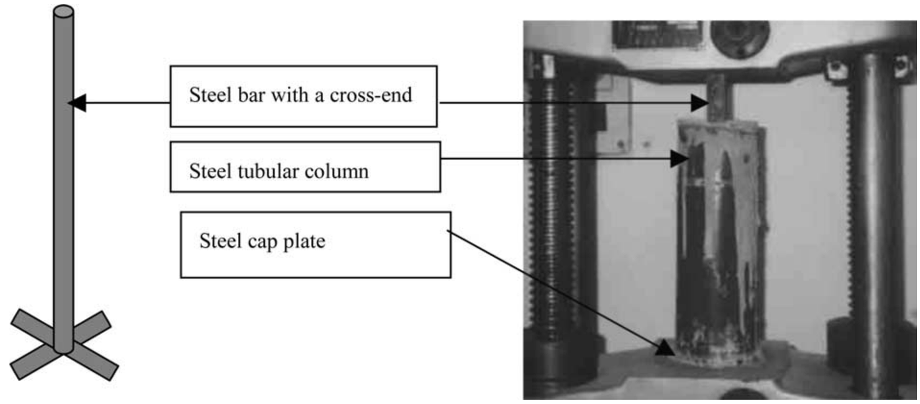



Fig. 1. Steel bar with a cross-end and schematic diagram of the specimen for testing of bond strength.

prepared for each mix at the age of 365 days, and these 1 cm × 1 cm × 1 cm samples were taken from the failed interface between concrete and steel tube after the bond strength test. At the same time the microstructure of concrete in the center zone for FCC4 and FCTs4 after compressive strength test also was also tested. All samples were kept in pure alcohol until testing, and were gold-coated before examination. These samples were observed under the S-2360N scanning electron microscope with an energy dispersive spectroscopy (EDS) analyzer.

## 3. Test results

### 3.1. Bond strength of CFTs

The test results of bond strength of concrete filled steel tubes modified by fly ash are shown in Fig. 2. It is observed that the addition of fly ash at low levels (FCTs1 and FCTs2) improves the bond strength at all tested ages, and the advantage of fly ash for bond strength is more remarkable when fly ash was coated on the inner face of steel tubes (FFTs). When the addition of fly ash reaches 40% (FCTs4), the bond strength before 56 days is lower than that of PCTs. Fig. 2 also shows the bond strength gain of the concretes between 28 and 365 days. FCTs4 have the highest strength gain of 39%, whereas FFTs have the lowest strength gain of 12%.

### 3.2. Compressive strength of CFTs

Typical load–axial displacement relationships of PCTs, FCTs4 and FFTs after 1 year curing are presented in Fig. 3. An improvement in the stiffness and the ultimate strength is observed when incorporating 40% fly ash by weight. The pre-coating of fly ash on the inner surface of the steel tube also lead to an improvement in the ultimate strength. During testing, the local bucking occurred mainly near the mid-section of the column for FCTs, however, for PCTs, local bucking occurred near both the mid-section and the end plates (Fig. 4).

Fig. 5 shows the test results of compressive strength of concrete filled steel tubes modified by fly ash. It can be found from Fig. 5 that the pre-coating fly ash to the inner face of steel tubes will slightly improve the compressive strength of CFTs, the maximum increase of compressive strength was found to be 5.2%. The strength of CFTs varied with the replacement amount of fly ash and the curing ages. At early ages, a high-level addition of fly ash

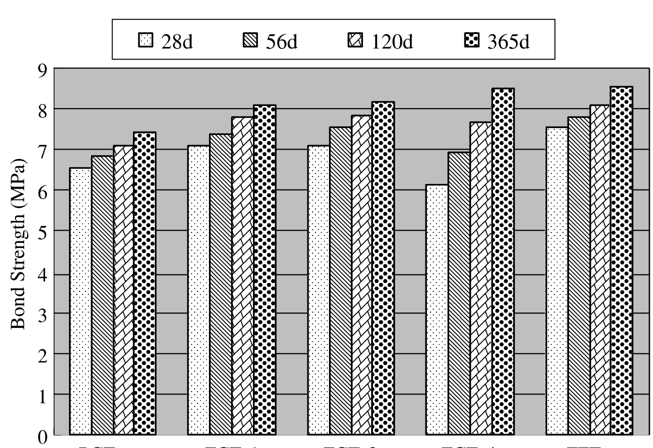



Fig. 2. Test results of bond strength of concrete filled steel tubes with fly ash.

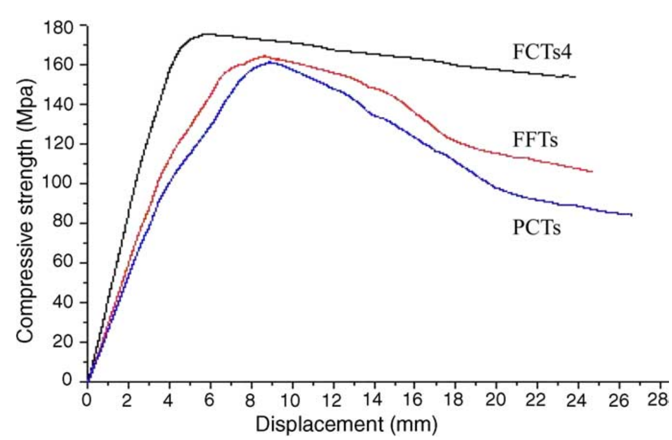



Fig. 3. Typical load–displacement curves of concrete filled steel tubular columns after 1 year curing.


Fig. 4. Typical failure modes of CFT columns after 1 year curing.

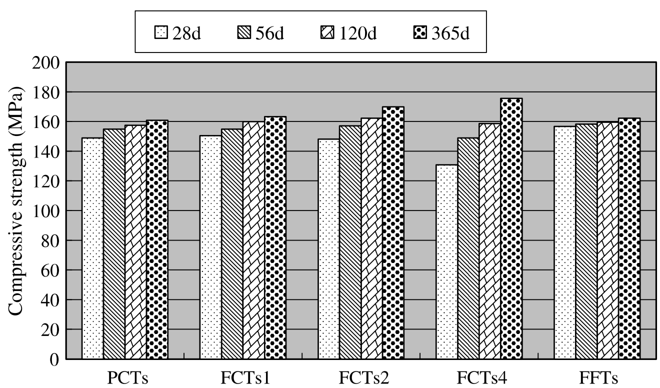



Fig. 5. Test results of compressive strength of concrete filled steel tubes with fly ash.

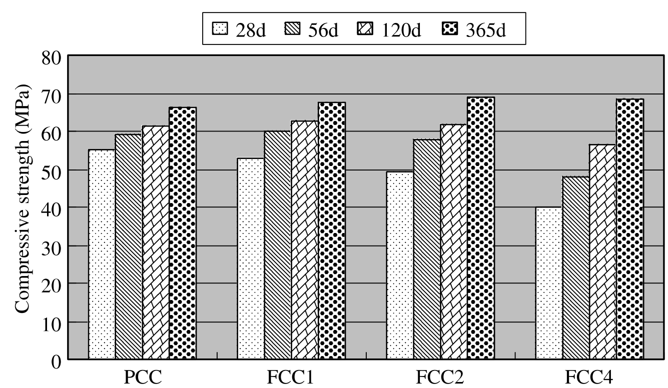



Fig. 6. Test results of compressive strength of concrete incorporating fly ash.

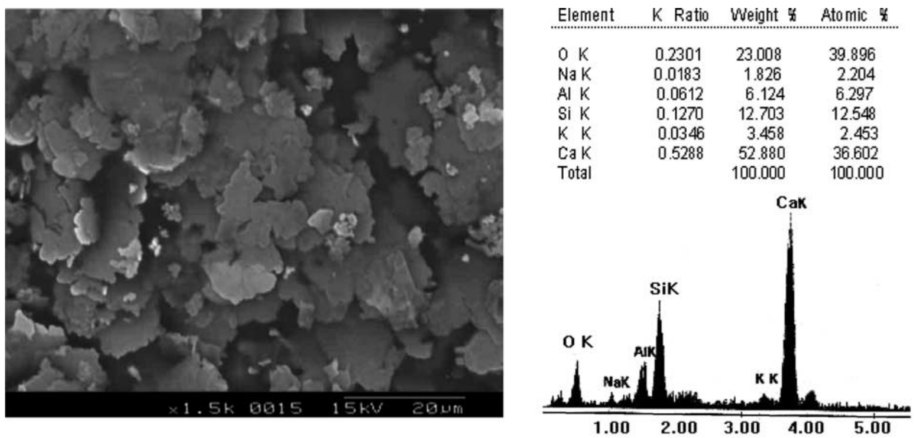
decreased compressive strength; the maximum decrease in strength was found to be 12.2%. After 365 days curing, a high-level addition of fly ash increased more the compressive strength of concrete filled steel tubes, the maximum increase in strength was found to be 9.2%.

### *3.3. Strength development of core concrete incorporating fly ash*

Fig. 6 shows the strength development of PCC, FCC1 (containing 10% FA), FCC2 (containing 20% FA) and FCC4 (containing 40% FA). From this figure, a general trend of increasing strength with age up to 1 year for all concretes can be seen. The 28-day strength decreases as the fly ash replacement levels increase. FCC4 has the lowest strength at 28 days, its strength is high at the end test age, and PCC has the highest 28-day strength, whilst its ultimate strength is the lowest.

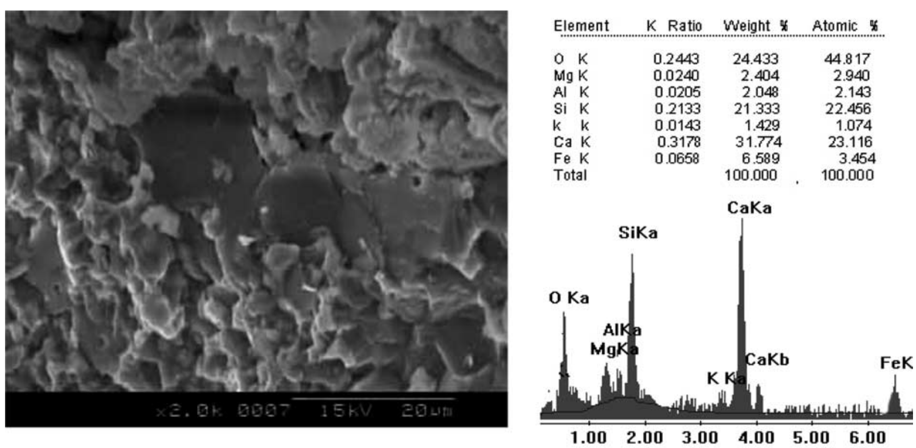
### *3.4. Microanalysis*

The typical SEM images and EDS data of the failed interface of PCTs, FFTs and FCTs4 after 1 year curing are shown in Figs. 7–9, respectively. Fig. 7 shows that C–S–H is much less dense in the interface of PCTs, and there are plenty of big air voids due to cement shrinkage upon drying (Fig. 7(a)). The EDX spectrum in Fig. 7(b) shows that Ca content is the highest at about 36.6%, while Si content is the lowest at about 12.5%; the Ca/Si ratio of 2.9 is the highest among these specimens. As shown in Fig. 8(a), the failed interface of FFTs 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. 8(b)) shows that Si content is 22.5%, and Ca content is about 23.1%; the Ca/Si ratio of 1.03 is about 1.8 times lower than that of PCTs. This result agrees well with Bentz et al. on the presence of silica fume or fly ash balancing the Ca/Si molar ratio in the interfacial zone [11,12]. The interface of FCTs4 is also composed of C–S–H (Fig. 9(a)), CH, Afm and AFt are not identified. An EDX spectrum (Fig. 9(b)) shows that Si content is about 20.5% and Ca content is 29.7%, and the Ca/Si ratio of 1.45 is much less than that of PCTs. Pores found in the interface of FCTs4 were filled by hydrating products, as shown in Fig. 10, the pores with 500 μm diameter



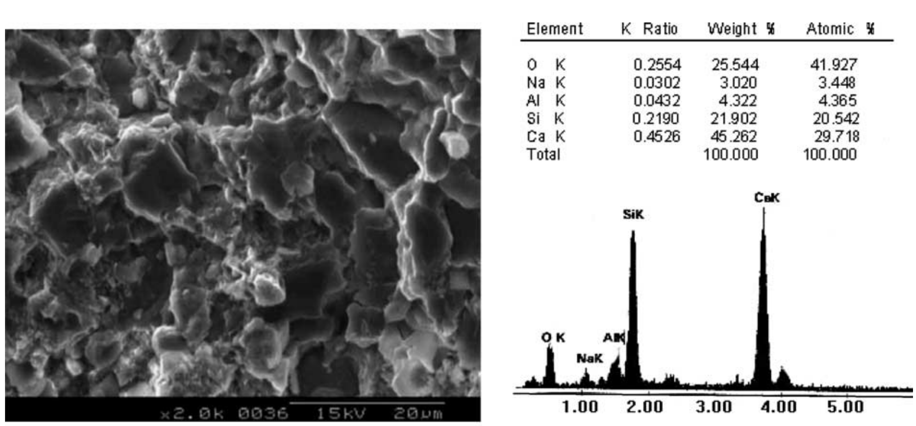

**(a)** SEM image of the interface **(b)** EDS image of the interface

Fig. 7. Typical SEM/EDS test results of PCTs after 1 year curing.




**(a)** SEM image of the interface **(b)** EDS image of the interface

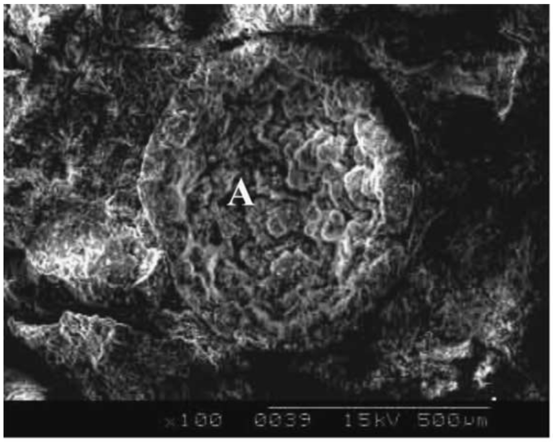
Fig. 8. Typical SEM/EDS test results of FFTs after 1 year curing.



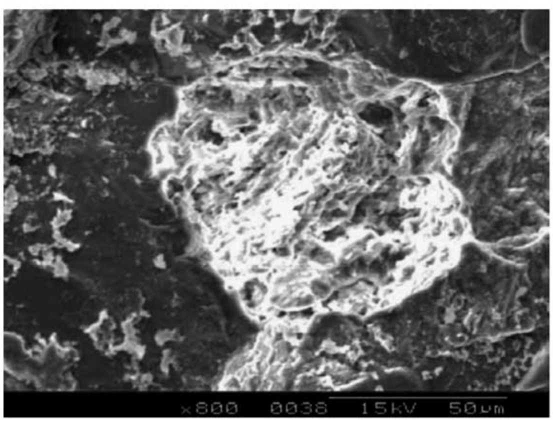

**(a)** SEM image of the interface **(b)** EDS image of the interface

Fig. 9. Typical SEM/EDS test results of FCTs4 after 1 year curing.

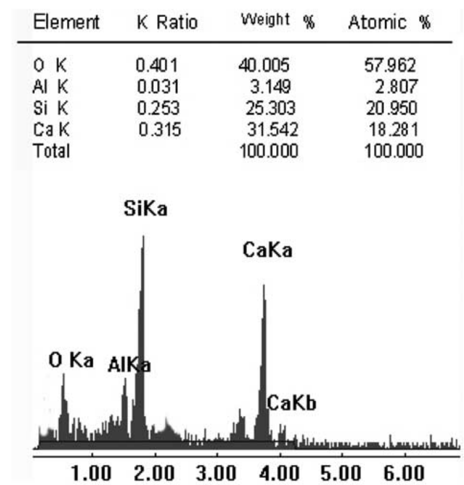
(Fig. 10(a)) or with 50 μm diameter (Fig. 10(b)), are filled by hydrating productions. An EDX spectrum at pore A (Fig. 10(c)) shows that Si content is 20.95%, while Ca content is about 18.28%, and the Ca/Si ratio is 0.87 which is due to the fact that the hydration product of fly ash is C–S–H. As shown in Fig. 11, a mass of un-hydrated fly ash




**(a)** SEM image of pore of the interface




**(b)** SEM image of pore of the interface




**(c)** EDS image of pore A

Fig. 10. SEM/EDS image of pores in the interface of FCTs4 after 1 year curing.

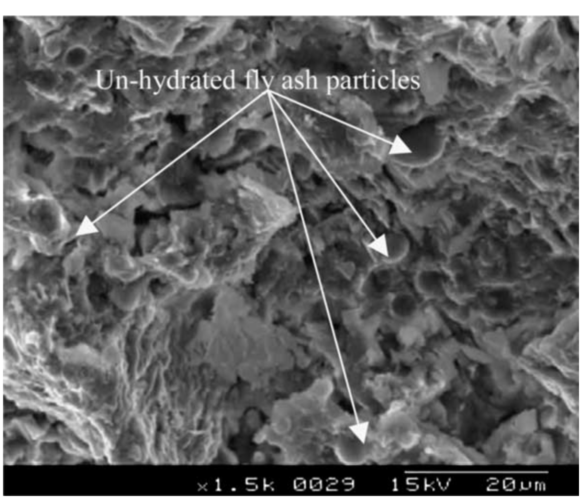



Fig. 11. SEM image of FCC4 after 1 year curing.

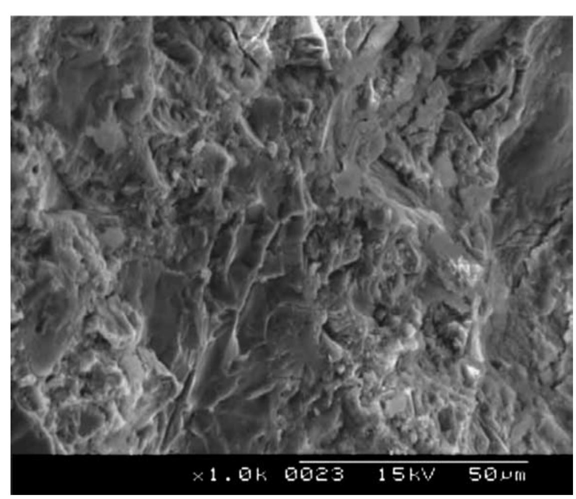



Fig. 12. SEM image of FCTs4 after 1 year curing.

particles have been found in the centre zone for FCC4. For FCTs4, however, there is little fly ash particle in the centre zone, and the microstructure was compact, as shown in Fig. 12.

## 4. Discussion

From the above analysis, it can be seen that the interface between steel tube and concrete for PCTs is porous, and the Ca/Si ratio is the highest. The reason is that the steel tube is a hydrophilic material and tightly sealed, the free water congregates near the surface of the steel tube. This leads to: (1) higher porosity near the interface, (2) more and larger hydrate crystals (such as CH, AFm and Aft), (3) the occurrence of debonding between the steel tubes and concrete. According to Ye [13], the existence of voids or the occurrence of debonding will impair the composite behavior of the steel tube and concrete, and result in the occurrence of eccentric compression and the appearance of instability even if under uniform compressive forces.

When fly ash concrete is used, the pozzolanic 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 that lead to increase bond strength. We can see that the bond strength of FCTs1 and FCTs2 is higher than that of PCTs at each test age (Fig. 2). The increased bond strength further decreases the occurrence of eccentric compression and instability, which led to increase of the compressive strength. At the same time, fly ash reduces the porosity of the core concrete, which, in turn, leads to increase of overall compressive strength.

Because of the low pozzolanic activity of fly ash, both the bond strength and the compressive strength of FCTs4 were lowest before 120 days when 40 wt% fly ash incorporated. However, at the age of 365 days, due to the pozzolanic reaction of fly ash and hydrating products filling the pores (Fig. 10) near the interface and in the concrete, both the bond strength and the compressive strength are relatively high. The high strengths lead to a high stiffness and a high resistance to local bucking for the concrete filled steel tubular columns (Figs. 3 and 4). It is interesting to find that the strength development of concrete filled steel tubular columns incorporating fly ash (Fig. 5) is higher than that of core concrete (Fig. 6) cured in the laboratory. This may be due to the humidity (which affects the reaction rate) in steel tube higher than that in laboratory, as shown in Figs. 11 and 12, the amount of un-hydrated fly ash in the centre zone for FCC4 cured in air is greater than that for FCTs4, and the confining effect of steel tube.

For the case of steel tube coated with a layer of fly ash (FFTs), the bond strength is the highest at each test age. This is due to the fact the pozzolanic reaction of fly ash increases the content of C–S–H in the interface, and fly ash reaction with the congregated water near the surface of steel tube reduces the water–cement ratio and the number of voids in the interface. The higher compressive strength of FFTs than that of control concrete filled steel tubes (PCTs) at all test ages is due to: (1) the increased bond strength reduces the occurrence of eccentric compression and unsteadiness and leads to the increase of the compressive strength, (2) the decrease of porosity near the interface leads to the increase of compressive strength for concrete local to the steel tube and thus leads to the increase of the overall compressive strength. However, the ultimate compressive strength of FFTs is lower than that of fly ash concrete filled steel tubes (FCTs), this is because the concrete in FFTs incorporated no fly ash, and the ultimate strength of control Portland cement concrete is lower than that of fly ash concrete after 1 year curing. The higher bond strength and compressive strength for FFTs than that of control PCTs leads to a higher stiffness and a higher resist-local buckling for FFTs.

## 5. Conclusions

The micro-structure and mechanical properties of fly ash concrete filled steel tubular columns with an aspect ratio of 3:1 have been investigated systematically. The mechanical properties of these composites were investigated and compared to control Portland cement concrete filled steel tube columns and FFTs with pre-coating of the inner surface of steel tube with a layer of fly ash. It is found that both bond strength and compressive strength for CFTs can be improved by pre-coating a thin layer of fly ash and the addition of fly ash. The early strength is weakened when high-level fly ash is incorporated; however, the ultimate strength is significantly improved, and the improvement of strength leads to a higher stiffness and a better resistance to local bucking for concrete filled steel tubular columns. When fly ash was used (both for the addition of fly ash and the pre-coating fly ash), the interface of CFTs is composed of dense C–S–H, no CH, Afm or AFt can be identified, and the Ca/Si ratio is low. A porous structure of C–S–H is observed at the interface of control concrete filled steel tubes (PCTs) and a high Ca/Si ratio is identified. For concrete cured in laboratory, the 40 wt% fly ash concretes have a low early-age compressive strength and a high 1-year strength. The strength development for high-level fly ash concrete cured in laboratory is lower than that for concrete filled in steel tube, plenty of un-hydrated fly ash is observed in the concrete center when cured in laboratory, whereas little unhydrated fly ash can be found in fly ash concrete filled steel tubular columns. Additional research is necessary for making general conclusions that extend to the more common case, where the column aspect ratio is much larger than 3:1.

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