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Effect of circulating fluidized bed combustion ash on the properties of roller compacted concrete

Maochieh Chi [a,*], Ran Huang [b]

[a] Department of Fire Science, WuFeng University, Chiayi 621, Taiwan, ROC
[b] Department of Harbour and River Engineering, National Taiwan Ocean University, Keelung 200, Taiwan, ROC

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ABSTRACT

Circulating fluidized bed combustion (CFBC) ash, which has such a high content of f-CaO and SO_3, is a waste or by-product of petroleum coke combustion power stations. The purpose of this study is to investigate the effects of CFBC ash on the properties of roller compacted concrete (RCC). CFBC ash was used to replace fine aggregate with various dosages (5%, 10% and 15%) by weight. All mixtures were designed according to ACI 211.3R and prepared for testing. During casting, cylinders were vibrated and compacted with different pressures of 25 g/cm^2, 50 g/cm^2 and 75 g/cm^2, respectively. Test results show that CFBC ash can increase the water absorption and effectively reduce the initial surface absorption. Meanwhile, CFBC ash has a positive effect on compressive strength, splitting tensile strength, and sulphate attack resistance of hardened RCC. SEM revealed that the main hydration products of specimens containing CFBC ash are AFt (ettringite), C–S–H (hydrated calcium silicate) and portlandite. Based on the presented observations and results, RCC with the dosage of 5% CFBC ash as fine aggregate replacement and the roller compaction pressure of 75 g/cm^2 is recommended.

1. Introduction

Circulating fluidized bed combustion (CFBC) is a very effective technology for power generation, which has met the environmental requirement for large reductions in SO_2 and NO_x emissions [1]. CFBC ash usually contains a higher content of calcium as an oxide and as a sulphate [2]. Many power stations use limestone as a sorbent for the SO_2 released during coal combustion. The limestone is calcined to a porous matrix of CaO in the furnace, where it reacts with SO_2 and O_2 to form $CaSO_4$. Ever since its commercialisation in the late 1970s, CFBC has grown gradually all over the world and has become the most widespread fluidized combustion design [3]. The market of CFBC installations for power generation is increasing continuously due to its excellent cost depollution. Therefore, the use and disposal of CFBC ash have posed challenges to both government and power plants [4–6].

Construction applications have been identified as one of the major uses for CFBC ash. These uses include structural fills, road base, synthetic aggregate and soil stabilization [7]. To qualify for these uses, the ashes must have special properties and pass certain ASTM tests. Xu et al. [4,5] indicated that CFBC ash might be utilised as an alternative source material for geopolymer synthesis via enhancing the reactivity by alkali and balancing the Na/Al ratio by additional aluminosilicate source. Shon et al. [8] found that the stockpiled CFBC ash could be used in developing controlled low strength material mixtures with restricted use of Portland cement and fly ash. Li et al. [9] pointed out that the modified CFBC desulfurization ashes can be utilised as an admixture as a result of its high activity in cement or concrete. However, the incorporation content of desulphurization ash in blended cements was controlled below 30%. Glinicki and Zielinski [10] found that a suitable air void system could be created when using CFBC fly ash for partial replacement of cement. CFBC ash is produced at lower combustion temperatures of 800–1000 °C which may lead to a less pozzolanic activity than the fly ashes produced at higher temperature [11]. Previous investigations have indicated that CFBC ash can be used to make no-cement concrete (NCC) with pressured fluidized bed combustion ash (PFBCA) or pulverized fuel ash (PFA) [1,7,12]. Another feasible application for CFBC ash is roller compacted concrete (RCC) which is low cement content and slump is close to zero [13–16].

RCC is an extremely dry concrete which is very difficult to compact by the normal methods used for workable concrete. It is usually used in the construction of dams and pavements. The usage of fly ash in RCC production was a widespread practice. Atis [17] has shown that high-volume fly ash concrete was an adequate material for both structural and pavement applications. Zhang and Qiu [18] have produced cement with CFBC ash and PFA which can attain about 32.5–42.5 MPa of compressive strength at the age

* Corresponding author. Tel.: +886 5 2267125x71415; fax: +886 5 2065112.
E-mail address: jackchi@wfu.edu.tw (M. Chi).

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of 28 days. Incorporating CFBC ash into RCC can further reduce the cost and meanwhile increase the total amount of binder in RCC.

CFBC ash meets neither North American standards nor European ones for components or additives in concretes [19]. ASTM requires that the SO_3 content of the ash cannot exceed 5% if the ash is to be used as a pozzolan. CFBC ash from the combustion of high sulphur coal will not conform to the SO_3 limits. This will restrict the use of CFBC ash. Therefore, CFBC ash is not suitable to be used as a cement replacement in concrete due to its unacceptably high sulphur content and the presence of free lime, large specific surface area, high water requirement, as well as harmful pores [7,20]. However, it can be used as a substitute for natural aggregates and often as a replacement for sand in the production of concrete blocks and in many countries used as a base in road construction [21–23].

Because of the speedy growth of CFBC technology and the amount of CFBC ash being approximately double that of normal pulverized coal combustion fly ash when generating equal electricity capacity due to the addition of sulphur-fixing agent and usage of low grade coal, the amount of CFBC ash will became lager and lager. For example, about 50 million tons of CFBC fly ash are discharged in China annually [24]. Over 13 million tons of fly ash are obtained in Turkey every year [13]. The volumes and disposal cost of CFBC ash have been increasing. Therefore, to secure its safe disposal or even better promote its utilisation in various applications is important and needed. The effective disposal or utilisation of CFBC ash has not been established in Taiwan. The Mailiao Six Light Naphtha Cracker Plant, located in the Yunlin county of Taiwan, produces on average approximately 0.8 million metric tons of CFBC ash per year and the amount of CFBC ash is increasing annually. However, little amount of it was utilised and relatively few studies have been reported on using CFBC ash as additive materials for concrete. Hence, how to develop a better use of CFBC ash is an urgent and important task. The purpose of this paper is to report the results of an experimental investigation carried out to study the effect of CFBC ash on the mechanical properties and the durability (characterised by water absorption test, initial surface absorption test, compressive strength, splitting tensile strength and sulphate attack resistance) of roller compacted concrete.

2. Experimental program

2.1. Materials

2.1.1. Cement

Type I ordinary Portland cement conforming to ASTM C150-05 [25] was used in this study. The specific gravity was 3.05. Initial and final setting times were 150 and 230 min, respectively. The blaine specific surface area was 3310 cm^2/g. The chemical compositions, physical properties and mechanical properties of Portland cement used are given in Table 1.

2.1.2. CFBC ash

CFBC ash of gray-and-white powder passing No. 200 (75 μm) account for about 86% of the particles. The specific gravity of CFBC ash were 2.50–2.70. The blaine specific surface area was 2880–3050 cm^2/g. The chemical elements of CFBC ash analysed with EDS were listed in Table 2. The chemical elements of CFBC ash comprise mainly oxygen, calcium, carbon and sulphur. The chemical compositions of CFBC ash are given in Table 3. It indicates that CFBC ash contains significantly higher amounts of calcium oxide (CaO), sulphur trioxide (SO_3), and loss on ignition (L.O.I.). Figs. 1 and 2 provides the SEM micrograph and XRD pattern of CFBC ash, respectively. From the SEM micrograph, CFBC ash comprise mainly coarse and angular, flaky, and irregular particles with a broad particle size range. XRD pattern shows the distinct presence of anhydrite ($CaSO_4$) and lime (CaO).

Table 1
Chemical compositions, physical properties and mechanical properties of cement.

Chemical compositions (%)	CNS 61	Test values (%)
Calcium oxide, CaO		63.8
Silicon dioxide, SiO_2		20.6
Aluminium oxide, Al_2O_3		5.4
Ferric oxide, Fe_2O_3		3.2
Magnesium oxide, MgO	Max: 6.0	2.0
Sulphur trioxide, SO_3	Max: 3.5	2.2
Loss on Ignition, L.O.I.	Max: 0.3	1.0
Physical properties of cement		
Specific gravity	3.15	3.05
Initial setting time (min)	Min: 45	150
Final setting time (min)	Max: 375	230
Specific surface (cm^2/g)	Max: 2800	3310
Air content (%)	Max: 12.0	8.2
Soundness (%)	Max: 0.80	0.05
Compressive strength (MPa)		
3-Days	Min: 12.35	20.6
7-Days	Min: 19.31	27.66
28-Days	Min: 27.54	37.67

Table 2
Chemical elements of the CFBC ash.

Element	Percentages (%)
O	45.68
Ca	32.30
C	10.21
S	10.10
Si	0.95
Al	0.45
Mg	0.31

Table 3
Chemical compositions of the CFBC ash.

Chemical compositions (%)	CFBC ash
CaO	55.84
SO_3	29.09
SiO_2	3.72
MgO	1.62
Fe_2O_3	0.57
Al_2O_3	0.55
K_2O	0.34
Na_2O	0.10
L.O.I.	7.83

2.1.3. Aggregates

The fine aggregate used was river sand with a fineness modulus of 2.56. The absorption value is 1.61% and its relative density at the saturated surface dry (SSD) condition is 2.56. In this study, CFBC ash was used, not as partial cement replacement, but as partial sand replacement for each group of concrete mixture. Before mixing and preparing specimens, fine aggregates replaced by CFBC ash at 0%, 5%, 10% and 15% replacement levels were mixed firstly. The grading curve of fine aggregates mixed with four different amounts of CFBC ash was showed in Fig. 3. The trend in the figure is one of higher fines content with increasing replacement of fine aggregate with CFBC ash. The coarse aggregate used was crushed stone with a fineness modulus of 6.33. The absorption value is 0.81% and its relative density at the saturated surface dry (SSD) condition is 2.68.

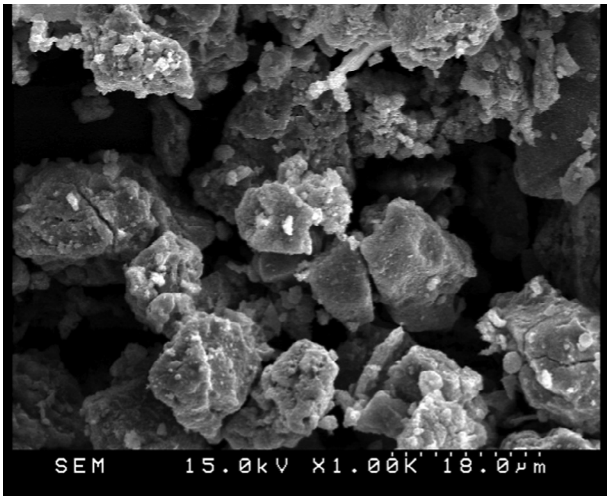

Fig. 1. SEM micrograph of CFBC ash (×1 K).

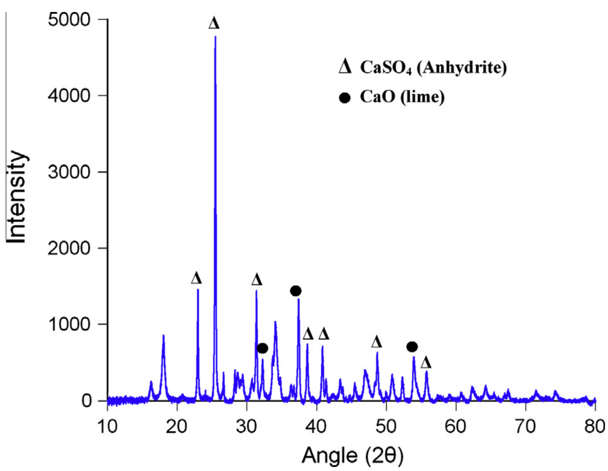

Fig. 2. XRD pattern of CFBC ash.

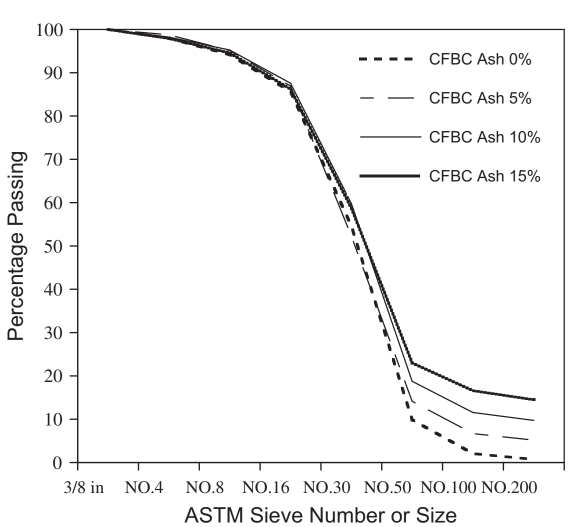

Fig. 3. Grading curve of fine aggregate mixed with four different amounts of CFBC ash.

2.2. Concrete mixture compositions and specimens preparation

For the purpose of investigating the effects of CFBC ash on the properties of roller compacted concrete, mixed concretes were produced using CFBC ash as fine aggregates replacement at the level of 0%, 5%, 10% and 15% by weight. Details of mixture proportions are given in Table 4. All RCC mixtures were designed according to ACI 211.3R. The water content corresponding roughly to the optimum water content was equal to 149 kg/m^3, and the cement content was equal to 270 kg/m^3. The water to binder ratio was kept at 0.55. Concrete cylinders of size 100 mm diameter and 200 mm height were cast. During casting, the cylinders were vibrated and compacted with the pressures of 25 g/cm^2, 50 g/cm^2 and 75 g/cm^2, respectively. After 24 h, the specimens were removed from the mould and moved into a curing room with 23 °C temperature until the time of testing.

2.3. Methods

2.3.1. Vebe consistometer test

The Vebe time test is a test for workability which measures the work needed to compact the concrete. The freshly mixed concrete is packed into a similar cone to that used for the slump test. The cone stands within a special container on a platform, which is vibrated at a standard rate, after the cone has been lifted off the concrete. The time taken for the concrete to be compacted is measured. The Vebe time test gives useful results for stiff concretes. The consistency of freshly mixed concrete was measured by using Vebe consistometer according to ASTM C1170 [26].

2.3.2. Water absorption

Water absorption values were made in accordance with ASTM C642 [27]. After the required curing period, the specimens were dried in an oven at 105 ± 5 °C for 24 h. The dry weight (W_d) was recorded and specimens were then immersed in water at 20 °C until they achieved a constant weight (W_s). Ws was taken as the saturated weight. It took up to 24 h for the specimens. The water absorption (WA) was then calculated by the following formula:

$$\text{Water absorption}: \mathrm{WA}(\%) = (W_s - W_d)/W_d \times 100 \qquad (1)$$

2.3.3. Initial surface absorption test (ISAT)

The initial surface absorption test (ISAT) on cylinders of size 100 mm diameter and 50 mm height was used to measure the absorptive characteristic of the surface layer of specimen in accordance with BS 1881-208 [28]. After the specimens cured for 28 days, the specimens were oven dried at 105 ± 5 °C to constant weight prior to the test. This test measures concrete permeability and its ability to absorb water during a prescribed period (ranging between 10 min and 2 h) under a head of 200 mm (8 in.). The rates of absorption of water at 10, 30, 60 and 120 min from the start of test were recorded. The rate of initial surface absorption is expressed in milliliters per square metre per second (ml/m^2 s).

2.3.4. Compressive strength test

For each mixture, the cylinders of size 100 mm diameter and 200 mm height were prepared and three specimens of each mixture were tested at the ages of 3, 7 and 28 days according to ASTM C39 [29].

2.3.5. Splitting tensile strength test

For each mixture, the cylinders of size 100 mm diameter and 200 mm height were prepared and three specimens of each mixture were tested at the ages of 3, 7 and 28 days according to ASTM C496 [30].

Table 4
Mix proportions of roller compacted concrete.

Mix no.*	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	CFBC ash (kg/m^3)
P25C00	149	270	744	1269	0
P25C05	149	270	706.8	1269	37.2
P25C10	149	270	669.6	1269	74.4
P25C15	149	270	632.4	1269	111.6
P50C00	149	270	744	1269	0
P50C05	149	270	706.8	1269	37.2
P50C10	149	270	669.6	1269	74.4
P50C15	149	270	632.4	1269	111.6
P75C00	149	270	744	1269	0
P75C05	149	270	706.8	1269	37.2
P75C10	149	270	669.6	1269	74.4
P75C15	149	270	632.4	1269	111.6

* Within mixture designation PxxCyy, xx represents the compaction pressure (in g/cm^2) and yy represents the level of replacement (in wt%) of CFBC ash as fine aggregate.

2.3.6. Resistance to sulphate attack

The concrete's resistance to sulphate attack was evaluated following the ASTM C88 [31]. After casting, the demoulded specimens were immersed in saturated sodium sulphate solution (pH = 8.7) for 24 h. Then the specimens were dried in an oven at 105 ± 5 °C for 24 h. This test cycle was repeated 5 times to investigate the effect of sulphate attack on the compressive strength.

2.3.7. X-ray diffraction (XRD) analysis

Randomly oriented powder specimens (about 1 gram weight) for XRD analysis were prepared by grinding small portions of the dried specimens. XRD graphs were obtained by a Panalytical DY2611 diffractometer using Cu Kα radiation at room temperature. The diffractograms were scanned from 10° to 70° in the 2θ and scanning rate was at 0.05° intervals.

2.3.8. Scanning electron microscopy (SEM)

The specimens with dimensions of 10 mm × 10 mm × 3 mm were prepared. Prior to SEM analyses, representative samples were air-dried and prepared using double-sided carbon tape. SEM analyses were performed using a HITACHI S-4800 microscope with an energy dispersive Spectroscopy (EDS).

3. Results and discussion

3.1. Vebe time

Roller compacted concrete (RCC) is a dry concrete material which is different from conventional concrete in its required consistency. In such stiffer mixtures, the variance of different workability cannot be sensibly detected by the slump test. The Vebe consistometer is recommended to measure the Vebe time for such dry mixtures. The results of Vebe time as shown in Table 5 indicated that Vebe time increased with an increase of CFBC ash replacement percentage in fresh concrete. As a result, CFBC ash decreased the workability of the fresh concrete. CFBC ash comprises mainly coarse and angular, flaky, drossy and irregular particles with a broad particle size range [32]. These characteristics of the CFBC ash such as the particle size, the specific surface area, and the shape might result in the need for a higher water requirement, which is why increasing CFBC ash replacement for fine aggregate decreased the workability of the fresh concrete. With the exception of the mixture containing CFBC ash with fine aggregate replacement of 15%, Vebe values satisfy the ACI 207.5R suggestion.

Table 5
Vebe time of CFBC ash with fine aggregate replacement.

Mix no.	Vebe time (s)
C00	12
C05	16
C10	35
C15	50

3.2. Water absorption

Percentage of water absorption is a measure of pore volume or porosity in hardened concrete, which is occupied by water in saturated conditions. Results are shown in Fig. 4. It indicates that water absorption of concrete increases with an increase of CFBC ash contents. The high water absorption of the mixtures containing CFBC ash is due to the porous and irregular surface of the CFBC ash, which results in the water absorption being increased. In addition, water absorption of concrete has a slight decrease with the increase of compaction pressure. The increasing compaction pressure decreases the porosity of concrete, hence it decreases water absorption.

3.3. Initial surface absorption test

The variations of initial surface absorption with respect to time for all RCC compacted with the pressures of 25 g/cm^2, 50 g/cm^2 and 75 g/cm^2 are given in Figs. 5–7. Results show that the initial surface absorption values of all RCC decrease with testing time. The initial surface absorption values drop sharply for the first 30 min, then slow down after one hour. As shown in Fig. 5, it can be seen that the mixes with 5% CFBC ash have the lowest initial surface absorption values, followed the control mixes without CFBC ash contents, while the highest initial surface absorption values are those of the mixes with 15% CFBC ash contents. As shown in Figs. 6 and 7, the ISAT results of mixes compacted with the pressures of 50 g/cm^2 and 75 g/cm^2 are similar to that of specimens compacted with the pressures of 25 g/cm^2. However, the higher compaction pressure leads to decrease of the initial surface absorption due to the reduction of permeable voids. The mixes containing CFBC ash with fine aggregate replacement of 5% can effectively reduce the initial surface absorption as a result of the higher content of f-CaO and SO_3 which is beneficial to the generation of more C–S–H and AFt. But for the mixes containing CFBC ash with fine aggregate replacement of 10% or 15%, the initial surface absorption values were higher than those of the control mixes.

3.4. Compressive strength

The compressive strength of the roller compacted concretes are presented in Figs. 8–10. It can be seen that compressive strength

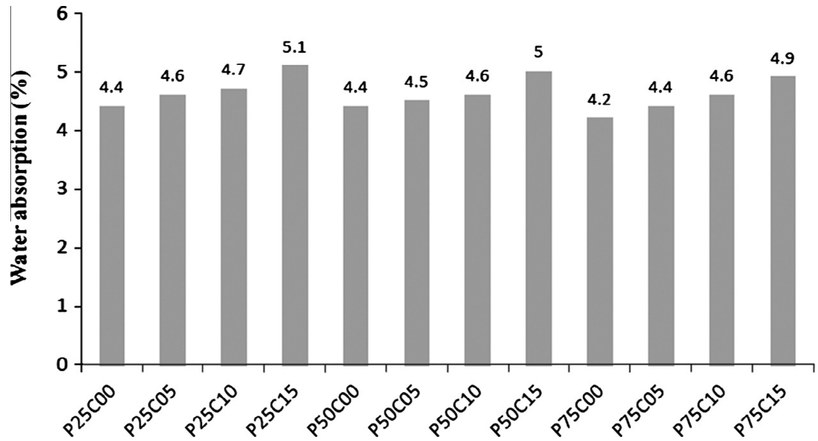

Fig. 4. Water absorption of mixes with different amounts of CFBC ash and compaction pressures.

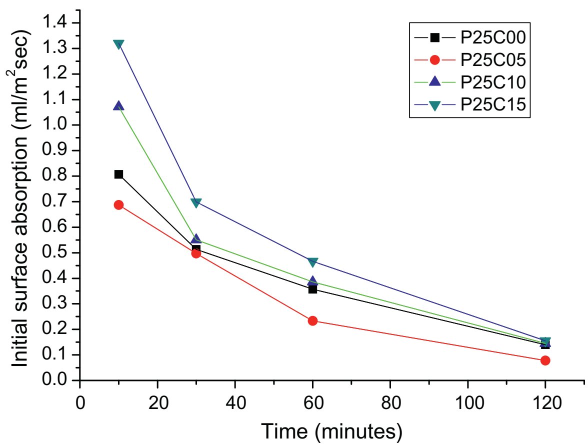

Fig. 5. Effect of CFBC replacement rate on initial surface absorption (for a compaction pressure of 25 g/cm^2).

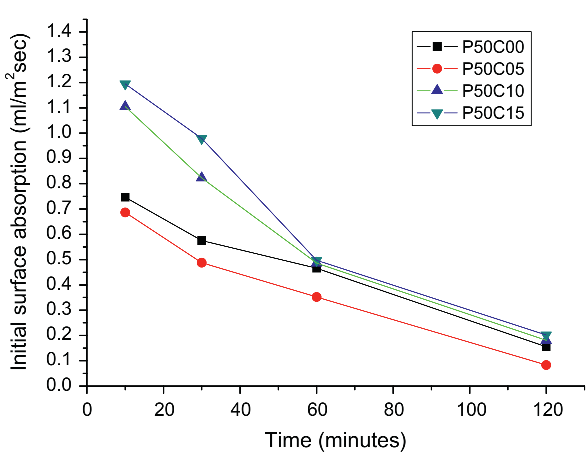

Fig. 6. Effect of CFBC replacement rate on initial surface absorption (for a compaction pressure of 50 g/cm^2).

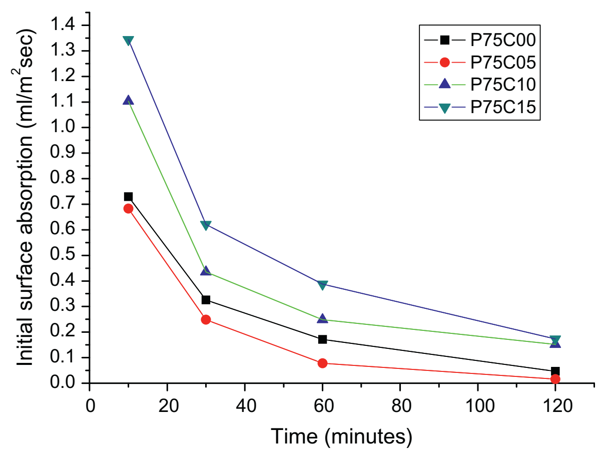

Fig. 7. Effect of CFBC replacement rate on initial surface absorption (for a compaction pressure of 75 g/cm^2).

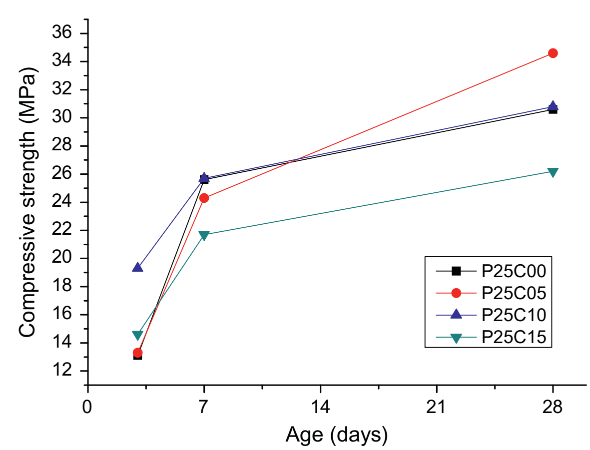

Fig. 8. Effect of CFBC replacement rate on compressive strength (for a compaction pressure of 25 g/cm^2).

increases with an increase of compaction pressure and the age of concrete. All RCC with different compaction pressures have the similar trend on compressive strength. As shown in Fig. 8, the specimens containing CFBC ash with fine aggregate replacement of 10% have a higher compressive strength than any others at the ages of 3 and 7 days. However, the specimens containing CFBC ash with fine aggregate replacement of 5% have the highest compressive strength at the age of 28 days. The main factors that affect the contribution of CFBC ash additives on compressive strength may be the filler effect and the higher content of f-CaO and SO_3. Freidin [33] has reported that a high f-CaO and high SO_3 content fly ash has good self-cementitious properties and the compressive strength

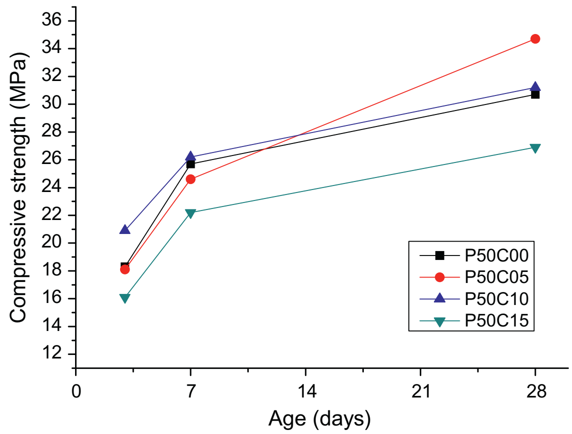

Fig. 9. Effect of CFBC replacement rate on compressive strength (for a compaction pressure of 50 g/cm^2).

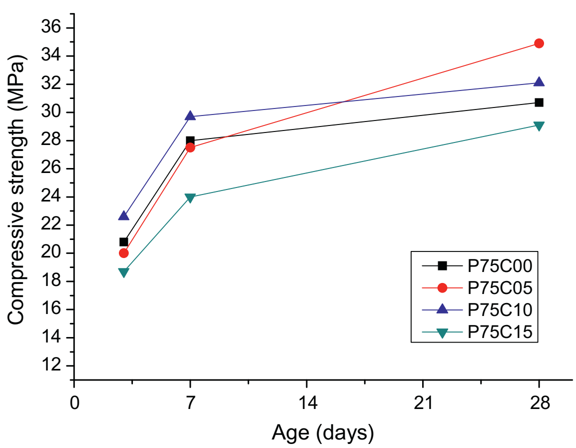

Fig. 10. Effect of CFBC replacement rate on compressive strength (for a compaction pressure of 75 g/cm^2).

can develop gradually. The specimens containing CFBC ash with fine aggregate replacement of 5% and 10% show an increase on compressive strength compared with the specimen without CFBC replacement at the age of 28 days. But the specimens containing CFBC ash with fine aggregate replacement of 15% showed a lower compressive strength compared with the control specimen without CFBC replacement at the ages of 3, 7 and 28 days. The porous and irregular CFBC ash particles have a larger specific surface area than spherical particles, which results in the water added to the mortar with CFBC ash being increased if the same fluidity is reached. The use of CFBC ash in concrete may result in structural damage and strength decrease [20,34], which is the reason that the utilisation percent of CFBC ash is limited.

3.5. Splitting tensile strength

The splitting tensile strength developments of roller compacted concretes are shown in Figs. 11–13. It shows that the splitting tensile strength increases with an increase of compaction pressure and the age of concrete. The specimens without CFBC ash have a higher splitting tensile strength than those containing CFBC ash with fine aggregate replacement except the specimens with fine aggregate replacement of 5% (P25C05 and P50C05) at the ages of 28 days. The results indicate that CFBC ash has not a positive effect on split tensile strength. From the compressive and splitting tensile strengths data obtained, it could be concluded that CFBC ash might be used in concrete between 5% and 10% as fine aggregates replacement.

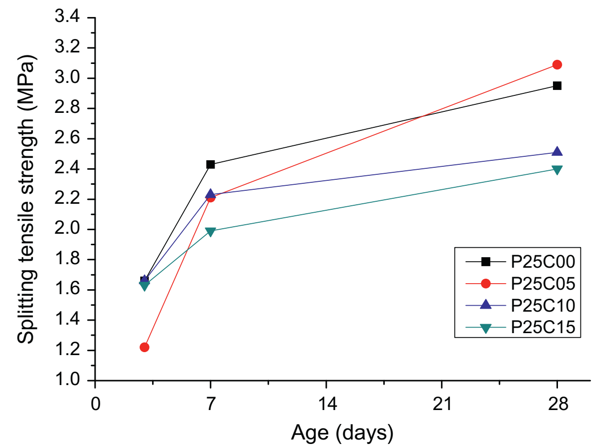

Fig. 11. Effect of CFBC replacement rate on splitting strength (for a compaction pressure of 25 g/cm^2).

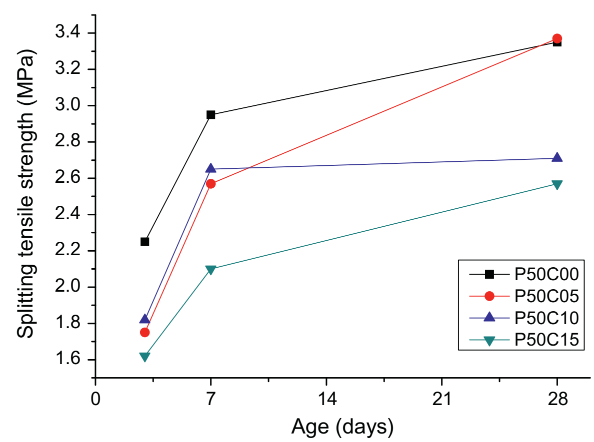

Fig. 12. Effect of CFBC replacement rate on splitting strength (for a compaction pressure of 50 g/cm^2).

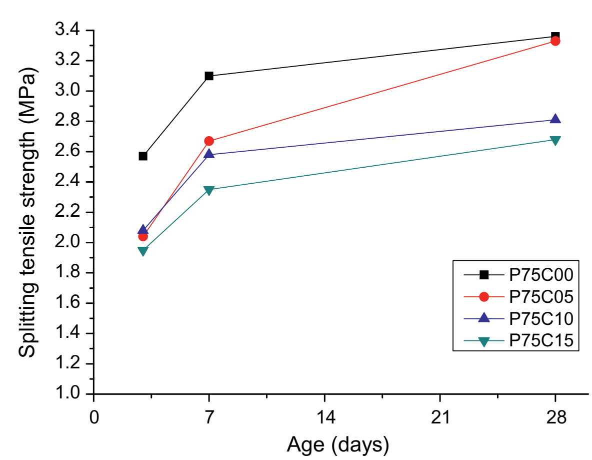

Fig. 13. Effect of CFBC replacement rate on splitting strength (for a compaction pressure of 75 g/cm^2).

3.6. Sulphate attack resistance

Sulphate attack on concrete may induce expansion, cracking, and spalling. The sulphate attack is generally attributed to the formation of expansive ettringite and gypsum, which are known to precipitate by through-solution mechanism [35]. The test results of sulphate attack based on five cycles were illustrated in Table 6. After exposure the sodium sulphate attack, the compressive strengths of roller compacted concretes containing 0% and 5% CFBC ash had a decrease ranged from 3.47% to 10.66%. However, the mixtures containing 10% and 15% CFBC ash had an increase ranged from 11.1% to 18.7% in compressive strengths. It may be said that the increase in compressive strength is attributed to the pore refinement process occurring due to the $CaSO_4$ products blocking the pores. The filler action due to the $CaSO_4{\cdot}2H_2O$ densities the pore structure to enhance the resistance to sulphate attack. The mineralogical analysis of CFBC ash as fine aggregate replacement of 10% and 15% after exposure the sodium sulphate attack is presented in Fig. 14. XRD pattern of CFBC ash as fine aggregate replacement shows the distinct presence of quartz, gypsum, Portlandite and ettringite. When specimens containing CFBC ash are exposed to the solution of sodium sulphate for a period of time, a significant amount of quartz has reacted with sulphur oxides (SO_2), lime (CaO) and calcium hydroxide ($Ca(OH)_2$) and the formation of anhydrite occurs. Then the soluble anhydrite converts into gypsum ($CaSO_4{\cdot}2H_2O$). The reactions of hydration can be written as follows [36].

$$CaO + H_2O \rightarrow Ca(OH)_2 \tag{2}$$

$$2Ca(OH)_2 + H_2SO_4 \rightarrow CaSO_4 \cdot 2H_2O \tag{3}$$

3.7. Scanning electron microscopy (SEM)

The SEM images of mixed concretes containing CFBC ash as fine aggregate replacement materials of 0%, 5%, 10% and 15% are shown in Figs. 15–18. As shown in Fig. 15, the specimen without CFBC ash contains only C–S–H gel after 28 days of hydration. Figs. 16–18 exhibit an appearance far different from that of specimen without CFBC ash. After 28 days of hydration, CFBC ash particles reacted with calcium hydroxide, resulting in the formation of C–S–H gel and needles. In addition, many AFt crystals grow mixed with C–S–H and can be found in the specimens containing CFBC ash as fine aggregate replacement materials of 5%, 10% and 15% at the age of 28 days. This observation is in agreement with the results reported by Sheng et al. [37]. Higher content of f-CaO and SO_3 is beneficial to the generation of more C–S–H and AFt. A higher content of CFBC ash provides more f-CaO and SO_3 for AFt growth. However, the compressive strength did not increases with an increase of CFBC ash due to the high replacement of fine aggregate

Table 6
Compressive strength of all mixes before and after sulphate attack.

Mix no.	Compressive strength (Mpa)		Strength reduction rate (%)
	Before	After	
P25C00	30.6	28.3	−7.52
P25C05	34.6	33.4	−3.47
P25C10	30.8	34.8	12.98
P25C15	26.2	29.1	11.06
P50C00	30.7	27.9	−9.12
P50C05	34.7	31.0	−10.66
P50C10	31.2	35.1	12.50
P50C15	26.9	31.2	15.99
P75C00	30.7	28.4	−7.49
P75C05	34.9	33.5	−4.01
P75C10	32.1	38.1	18.69
P75C15	29.1	33.8	16.15

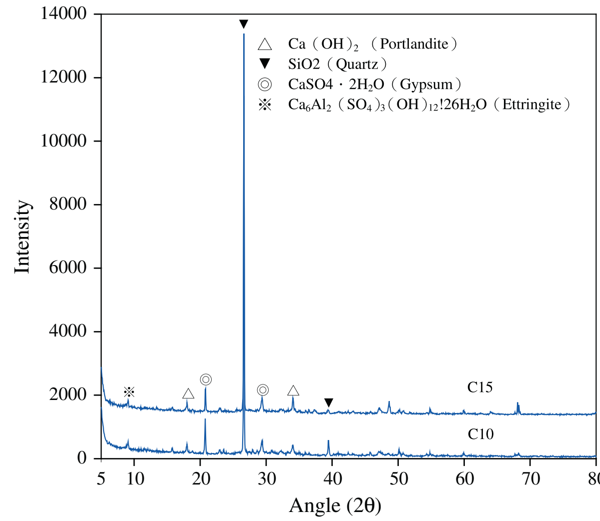

Fig. 14. XRD pattern of CFBC ash as fine aggregate replacement of 10% and 15% after exposure sodium sulphate attack.

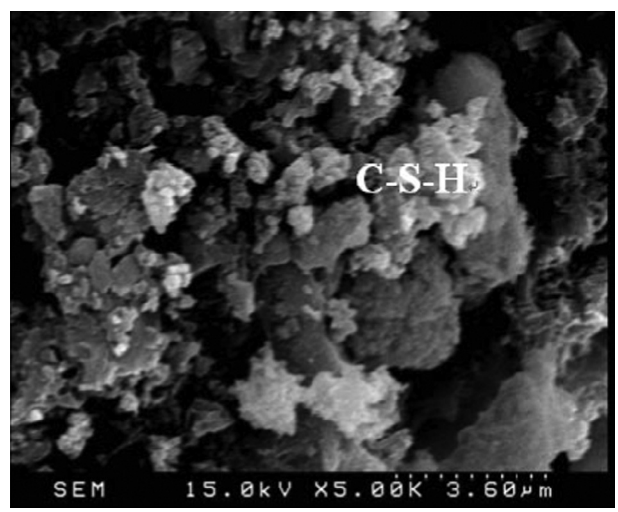

Fig. 15. SEM micrograph for the mixed specimen without CFBC ash (×5 K).

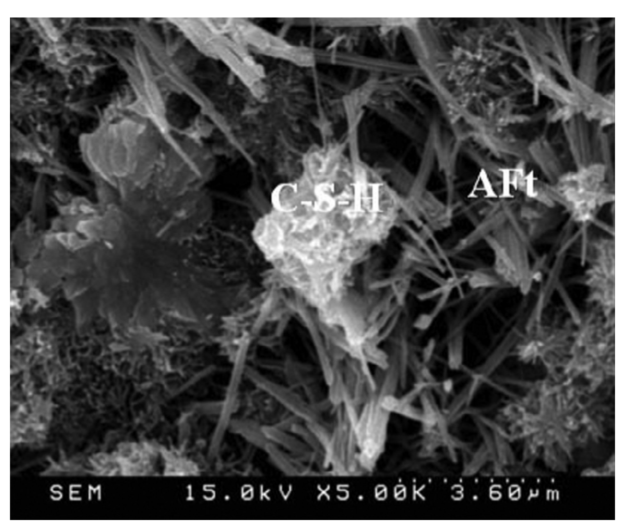

Fig. 16. SEM micrograph for the mixed specimen with 5% CFBC ash (×5 K).

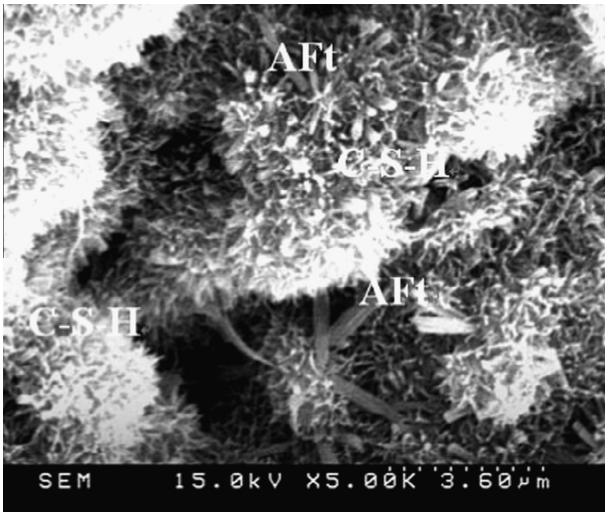

Fig. 17. SEM micrograph for the mixed specimen with 10% CFBC ash (×5 K).

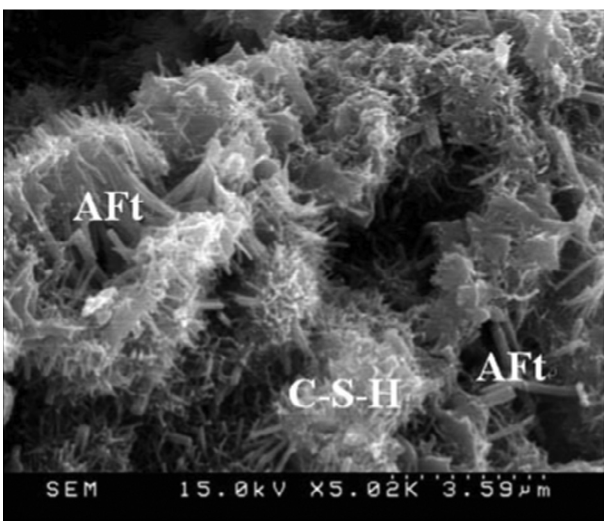

Fig. 18. SEM micrograph for the mixed specimen with 15% CFBC ash (×5 K).

by CFBC ash. Based on the test results mentioned above, 5% of CFBC ash replacement to fine aggregate is the optimal limit. At 15% CFBC ash replacement to fine aggregate, it could be only 5% CFBC ash acted as cementitious materials and 10% CFBC ash acted as fillers.

4. Conclusions

This study has proven that CFBC ash as fine aggregate replacement materials would have a significant influence on the properties of roller compacted concrete. From the test results, the following conclusions are made.

(1) CFBC ash comprise mainly coarse and angular, flaky, and irregular particles with a broad particle size range, which may decrease the workability of the fresh concrete. Vebe values satisfy the ACI 207.5R suggestion with the exception of the mixes containing CFBC ash with fine aggregate replacement of 15%.
(2) CFBC ash can increase the water absorption and effectively reduce the initial surface absorption because of its higher amounts of calcium oxide (CaO), sulphur trioxide (SO_3), and loss on ignition (L.O.I.).
(3) CFBC ash has a positive effect on compressive strength, splitting tensile strength, and sulphate attack resistance of hardened RCC.
(4) SEM revealed that the main hydration products of specimens containing CFBC ash are AFt (ettringite), C–S–H (hydrated calcium silicate) and portlandite.
(5) RCC with the dosage of 5% CFBC ash as fine aggregate replacement and the roller compaction pressure of 75 g/cm^2 is recommended based on the presented observations and results.

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