

# Sustainable Self-Compacting Concrete Containing High-Amount Industrial By-Product Fly Ash As Supplementary Cementitious Materials

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## Research Article

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# Abstract

Nowadays, utilizing large amount industrial by-product fly ash (FA) as the alternatives for cement in self-compacting concrete (SCC) had attracted more attention. In this study, FA was employed in SCC at five levels (0 %, 20 %, 30 %, 40 %, 50 %). The mechanical behaviors, the water porosity, the transport properties and the sustainability of FA series SCC were investigated. At the **initial** curing stage (3 days), the use of FA in SCC reduces mechanical properties, increases water porosity, water absorption and water absorption coefficient (sorptivity) of SCC. FA series SCC have the lower resistance against **carbon dioxide** attack, chloride ion penetration than cement -based SCC. The prolonging curing time is beneficial to improve the long-term behaviors of FA- blended SCC. After SCC made with 20 %, 30 %, 40 % FA water-curing for 90 days, there are an reduction of 0.44-2.09 % in the mechanical behaviors and an increase of 0.082-0.41 % in the water porosity, compared to pure-cement SCC. Beyond the content of FA (40 %), the **differences** of the mechanical properties and the water porosity between SCC with 50 % FA and fully cement SCC are below the value of 2.5 %. With the progress of the curing time, the largest reduction rates of the water absorption and the sorptivity were found in 50 % FA-blended SCC. Utilizing 50 % FA in SCC reduces the total charge passed values of SCC. The manufacture of 50 % FA-blended SCC has the lowest energy **consumption** and released amounts of CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub> in all SCC mixtures. The application of high-level FA in SCC is the positive assistance to prepare sustainable SCC with satisfying long-term behaviors.

## Introduction

Self-compacting concrete (SCC) was first developed in Japan between 1980 year and 1990 year. The technology of SCC represents an important advance in modern concrete industry (Ozawa et al. 1989). Fresh mixing SCC has three important features. First, SCC as a kind of high fluidity concrete can easily place by means of its own weight. Second, SCC adapts to cast in structures with complicated formwork, congested reinforcing bar and the difficult to reach areas without mechanical vibration. Third, fresh SCC can maintain the cohesive to prevent segregation or bleeding water during the transportation and the casting processes (Bouzoubaa and Lachemi 2001). The use of SCC in **construction engineering**s not only leads to the shortening of construction time and the reduction of **labor** cost, but also lowers the noise and the vibration levels on the building site (Nunes et al. 2006). Due to these advantages of SCC materials over normal vibrated concrete, SCC had been widely applied in large-scale buildings, high-speed roads, cross-ocean bridges, dams and marine **structures** (Ouchi 2001).

In general, SCC mixtures contain cement, fine and coarse aggregates, superplasticizer, water. The components to make SCC are similar to those for making normal concrete. However, in order to obtain high fluidity, a large number of cement needs to incorporate into SCC. The inclusion of excessive cement in SCC causes the serious environmental problems (Le et al. 2015). Menéndez et al. (2014) showed that the manufacture of cement clinker at each ton releases nearly one ton of greenhouse gas (CO<sub>2</sub>), which contributes about 5 % of CO<sub>2</sub> emissions in the worldwide. It is estimated that the total amounts of CO<sub>2</sub> deriving from cement production in the global areas are 1.35 billion tons every year. By 2025 year, CO<sub>2</sub> emissions of **cement industry** around the world increase by about 15-20 %, based on the current emission level (Anand et al. 2006). Also, the preparing process of cement produces a large number of kiln dusts (Blankendaal et al.2014). Other alternative technologies need to develop for the production of green and eco-friendly SCC.

In the last four decades, the researcher had explored the solution to **promote** the sustainability of SCC. The utilization of supplementary cementing materials (SCMs), i.e. fly ash (FA), ground granulated blast-furnace slag (GGBS), metakaolin (MK), silica fume (SF), rice husk ash (RHA), to replace cement in SCC are the promising option to lower the

negative influence of SCC [industry](#) on the environment (Arumugam and Shaik 2020). Among these SCMs, FA is the most commonly used SCMs. It is reported (Gollakota et al. 2019) that about 100 million tons FA were generated every year in China. Each year, the amount of FA produced in European was 66.7 million tons. The yield of FA per year in Turkey reached 24.6 million tons. The annual output of FA in the global is 750 million tons. Utilizing FA as the alternatives for cement to prepare SCC consumes a large [number](#) of industrial by-products and lowers the demand for cement, which is considerable beneficial to reduce environmental pollution in the production of SCC.

The previous studies had indicated that the common amount of FA in SCC is generally limited to 10-30 % of total binder materials. When large-level FA by mass (above 40 %) was applied in SCC, it is termed as high-amount FA SCC (Hemalatha and Ramaswamy 2017). FA at large amount incorporating into SCC may significant affect the behaviors of SCC mixture. The introduction of high content FA to SCC is the challenge for developing sustainable SCC. Jalal et al. (2019) proved that the presence of more FA in SCC had a positive role on the rheological behaviors of SCC, fresh mixing SCC with high-level FA had the satisfactory self-compacting properties. Moreover, the inclusion of large-amount FA in SCC can appreciably lessen the formwork lateral pressure and reduce the critical shear rate of fresh SCC (Gregori et al. 2008). The minimum viscosity, shear thickening intensity and the highest passing capacity of SCC were found in high-volume FA SCC (Güneyisi et al. 2015). Also, FA used to replace cement in SCC at high level causes the entrained air bubble of fresh mixing SCC more easily to escape (Puthipad et al. 2016). Besides, SCC mixture containing high-content FA needs a longer time to set than pure cement-based SCC (Güneyisi et al. 2009). As a result, the presence of high level FA in SCC delays the binder materials hydration at the initial stage and lowers the early age mechanical properties of SCC (Jalal et al. 2013). With the progress of the curing time, the maximum increase in the mechanical strength was observed in 90- days SCC with large content FA (Dinakar et al. 2013). At the late curing stage, SCC sample made with high-amount FA had the identical mechanical properties to normal SCC (Kuder et al. 2012). High-amount FA SCC has the lower hydration temperature, thermal stress and thermal expansion coefficient than pure-cement SCC (Utsi and Jonasson 2012; Abhijeet et al. 2015). Altoubat et al. (2017) indicated that the replacement of cement at high content with FA in SCC can compensate autogenous shrinkage of SCC, a reduction of 26 % in the dry shrinkage was found in SCC with 60 % FA. In addition, at the [actual environment](#), the chemical media in the environment (water, [carbon dioxide](#), chloride ion, sulfate ion) may penetrate inside FA series SCC by transport mechanism. Dinakar et al. (2008) showed that SCC made with high level FA had larger permeable void, water absorption and water absorption coefficient than fully-cement SCC. The increase level of FA lowers the resistance of SCC against CO<sub>2</sub> attack, and the largest carbonation depth was obtained in SCC mixture with 85 % FA at 90,365 days (Dinakar et al. 2009). Güneyisi et al. (2015) found that 28-days SCC sample with high-amount FA had the low gas permeability coefficient of SCC. The presence of high-level FA in SCC seems to be beneficial in preventing the chloride ion migration and penetration inside SCC (Sahmaran et al. 2009). Vishwakarma et al. (2020) [observed](#) that the use of high-level FA in SCC improves the resistance of SCC against sulfuric acid attack.

Up to now, there are some extensive studies on the application of FA at large amount in SCC. However, these literatures are main focus on the fresh and the mechanical properties of high-level FA SCC. The long-term transport behaviors and the porosity of large content FA-blended SCC had not fully discussed. The little information is available on the relationship between the porosity and the transport property [indexes](#) of FA series SCC. The [document](#) related to the sustainability of high -level FA SCC is insufficient. Further study needs to carry out on these aspects.

In this study, the industrial by-product FA was employed in SCC at five levels (0 %, 20 %, 30 %, 40 %, 50 %). At a regular curing time, the effect of FA content on the compressive strength and the flexural strength of SCC was evaluated. The transport behaviors of SCC mixtures with FA, i.e. the water porosity, the water absorption, the water absorption coefficient, the carbonation depth, the carbonation coefficient, the total charge passed values, were measured. The relationships between the water porosity and the compressive strength, the transport properties of FA-blended SCC

were assessed. The consumed energy efficiency and the environmental efficiency in the production of SCC were examined to discuss the sustainability of FA series SCC. The deep understanding how to utilize high-level FA as the valuable resource in SCC was obtained. It lays the foundation for the reasonable production of sustainable SCC with high-amount FA.

## Materials And Methods

### *Materials*

The primary binder material is Ordinary Portland cement (OPC) of ASTM Type I, complying with ASTM C 150-07 (ASTM C 150-07 2007). Class-F industrial by-product FA, meeting the specification of ASTM C 618-05 (ASTM C 618-05 2005), was used as SCMs, FA was provided by an electric power plant in Chinese. The oxide compositions, [mineral compositions](#) and physical properties of OPC, FA are shown in Table 1. A polycarboxylate-based (PCA) superplasticizer (SP) was used in all SCC mixtures. River sand fine aggregate (particle size < 5 mm) was obtained from China. Crushed limestone gravel with [continuous](#) gradation (particle size of 5-25 mm) was applied as coarse aggregate. The particle gradations, the physical properties of fine aggregate and coarse aggregate are presented in Table 2.

### *Composition of studied SCC*

In this study, two series SCC mixtures were prepared for the investigation. Control SCC is SCC with fully OPC (named as OPC100). The other series SCC mixtures are that FA replaces 20 %, 30 %, 40 %, 50 % OPC in SCC (labeled as OPC80FA20, OPC70FA30, OPC60FA40, OPC50FA50). In all SCC mixtures, the weight proportions of total binder materials (OPC + FA)/fine aggregate/ coarse aggregate/water were kept at 1:1.51:2.36:0.35. The amounts of total binder materials are 460 kg/m<sup>3</sup>. PCA SP in SCC is equal to 0.24 % mass of total binder materials. The details of the mix proportions of two series SCC are summarized in Table 3.

### *Sample preparation, curing conditions*

First, the solid components of SCC mixture were batched and dry-mixed for 60 sec. Then, PCA SP premixed with water was introduced to the solid mixtures, SCC mixture continued to mix for 300 sec. Before casting, the fluidity, the passing ability and the segregation ratio test were carried out to assess the fresh properties of SCC. Table.4 shows that the rheological properties of all SCC mixtures meet the target demand of fresh SCC, specified by EFNARC standard (EFNARC 2002). Finally, fresh SCC was poured into the moulds and transferred to the room with a temperature of 23 °C for 24 h, complying with GOST 10180 (GOST 10180 1990). After one day, SCC was demoulded and water-cured in an [environment](#) with the relative humidity of 93 ± 2 % and the temperature of 20 ± 3 °C until the age of testing.

### *Test methods*

After 3, 7, 28, 90 days of water-curing, three 100 mm × 100 mm × 100 mm cube samples were used to measure the compressive strength of SCC, according to BS EN 12390-3 (BS EN12390-3 2000). In the test, the compression machine with a maximum load of 3000 kN was applied. The flexural strength test of a three-point was conducted at a load rate of 0.04 N/ mm<sup>2</sup>·s, complying with the requirement of BS EN 12390-5 (BS EN 12390-5 2000) using three 100 mm × 100 mm × 400 mm prismatic SCC.

The vacuum saturating method was introduced to determine the water porosity of SCC (Khan et al. 2000). After cylindrical SCC sample of  $\Phi$  50 mm  $\times$  40 mm was cured in water for 3, 7, 28, 90 days, SCC sample was allowed to dry at a temperature of  $100 \pm 5$  °C. Then, SCC sample was kept at vacuum pressure for 3 h. Finally, SCC sample was left to submerge at the atmospheric pressure for 12 h. The formula (1) was used to calculate the water porosity of SCC.

$$P = \frac{(W_{sat} - W_{dry})}{(W_{sat} - W_{wat})} \times 100 \quad (1)$$

Where:  $P$  is the water porosity, in %;  $W_{sat}$  is the mass of saturated specimen in air, in kg;  $W_{dry}$  is the mass of oven-dried specimen at  $100 \pm 5$  °C, in kg;  $W_{wat}$  is the mass of saturated specimen in water, in kg;

ASTM C 642 method (ASTM C 642 2006) was used to test the water absorption of SCC. After  $\Phi$  100 mm  $\times$  50 mm cylindrical SCC sample was stored in water for 28, 90 days, SCC sample was dried in an oven with a temperature of  $100 \pm 5$  °C. Then, SCC sample cooled to room temperature was exposed to water for 45 min. Finally, the weight of SCC sample at surface-dry condition was recorded. The water absorption of SCC is the percentage of the weight gain of absorbed water of sample (45 min) to the weight of absolute-dry sample. The sorptivity of SCC was conducted using  $\Phi$  100 mm  $\times$  50 mm cylinder SCC sample, based on ASTM C 1585-04 (ASTM C 1585-04 2004). After water-curing for 28, 90 days, the top surface and the bottom surface of SCC sample were sealed, the other surfaces of SCC were kept to contact with water at a depth of 5 mm. The cumulative weight gain of SCC sample due to water absorption from 1 h to 96 h was recorded. The sorptivity of SCC was the curve slope of the cumulative weight gain and the square-root of time. The resistance of SCC against CO<sub>2</sub> attack was assessed by the accelerated carbonation test in accordance with GBJ 82-85 (GBJ 82-85 1985). Before the test, prismatic SCC sample of 100 mm  $\times$  100 mm  $\times$  300 mm was immersed in water for 26 days and allowed to dry at a temperature of 60 °C for 48 h. Then, SCC was placed into a accelerated carbonation chamber, where the temperature, the relative humidity, the concentration of CO<sub>2</sub> are  $20 \pm 3$  °C,  $50 \pm 5$  %,  $20 \pm 3$  %, the half face of SCC sample was exposed to CO<sub>2</sub> gas. Finally, the test was conducted at the exposure durations of 3, 7, 14, 28 days. The carbonation coefficient of SCC was obtained by the regression analysis on the carbonation depths of SCC sample at different exposure times. The rapid chloride ion permeability test (RCPT) was employed to evaluate the resistance of SCC against chloride ion penetration, in conformance with ASTM C 1202 (ASTM C 1202 2006). After  $\Phi$  100 mm  $\times$  50 mm cylinder SCC sample was stored in water for 28, 90 days, one face of SCC sample was in contact with the solution of 3.0 % NaCl, the opposite surface of SCC sample was exposed to NaOH solution of 0.3 N. A direct current of 60 V was exerted on sample for 6 h. The total charge passed values (in coulombs) through SCC sample over 6-h period were reported.

The consumed energy efficiency in the production of SCC (per m<sup>3</sup>) was obtained from the total embodied energy of each ingredient in SCC. Regarding the environmental efficiency of SCC, the released amounts of greenhouse (CO<sub>2</sub>) gas and pollutant gases (NO<sub>x</sub>, SO<sub>x</sub>) in the preparation of SCC (1 m<sup>3</sup>) were calculated by multiplying weight of raw materials.

## Results And Discussions

### *Compressive strength*

The compressive strength test results of SCC mixtures with 0 %, 20 %, 30 %, 40 %, 50 % at four periods (3, 7, 28, 90 days) are given in Fig.1. In case of control SCC and FA series SCC, the compressive strength of SCC mixtures develop during the curing period from 3 days to 90 days. Moreover, the inclusion of FA in SCC mixture results in the reduction

of the compressive strength of SCC. At the **initial** curing stage (3 days), FA replaces OPC in SCC at a low content (20 %, 30 %), the compressive strength of SCC are 37.83 MPa, 32.64 MPa, there are the reduction of 15.39 %, 26.99 % in the compressive strength, compared with 100 % cement-blended SCC (44.71 MPa). The increase in the amount of FA from 30 % to 40 %, 50 %, the notable large reduction rate on the compressive strength for 44.33 %, 52.25 % was found in 40 %, 50 % FA SCC. The **prolonging** curing period has a positive contribution on the long-term compressive strength development of FA series SCC. The 90-days compressive strength of SCC containing 0 %, 20 %, 30 %, 40 %, 50 % FA are 75.47 MPa, 75.12 MPa, 74.74 MPa, 74.15 MPa, 73.89 MPa. FA series SCC samples have 0.46 %, 0.97 %, 1.75 %, 2.09 % low compressive strength, compared to fully-cement SCC. With regard to the long-term compressive strength of SCC, the **differences** between pure-cement SCC and FA series SCC are **no significant**. High-amount FA (50 %) was incorporated into SCC, the reduction rate of the 90-days compressive strength is within the acceptable range (< 2.5 %). It may probably relate to this fact that FA has the low reaction activity at the early curing age, the replacement of cement with FA lowers the binder materials amount in SCC, the microstructures of SCC containing FA are homogeneous and looser than control SCC. With the progress of the curing period, FA SCM produces the secondary hydration reaction with **calcium hydroxide** from cement hydration, the continuous water-curing **accelerates** that the secondary hydration products of FA fill into the void of SCC (Vanyo et al. 1996).

### ***Flexural strength***

Fig.2 shows the flexural strength development of control SCC and FA-blended SCC mixtures as a function of the curing time. After two series SCC were stored in water for 3, 7, 28, 90 days, the flexural strength of SCC made by fully-cement is 7.95 MPa, 9.78 MPa, 11.68 MPa, 12.54 MPa. SCC mixtures incorporating 20 %, 30 %, 40 %, 50 % FA exhibit the flexural strength in the ranges of 7.76-6.54 MPa, 9.65-8.97 MPa, 11.54-11.27 MPa, 12.44-12.39 MPa, respectively. The flexural strength of SCC mixture grows at the curing ages of 3, 7, 28, 90 days. Moreover, the introduction of FA to SCC sample lowers the flexural strength of SCC. At the test period of 3 days, the flexural strength of 20 %, 30 %, 40 %, 50 % FA-blended SCC have the reduction of 2.39 %, 7.04 %, 12.20 %, 17.74 %, in comparison to 100 % cement-based SCC. With the extension in the curing time from 3 days to 90 days, the 90-days flexural strength of SCC with 0 %, 20 %, 30 %, 40 %, 50 % FA experience the increase for 57.74 %, 60.95 %, 68.61 %, 78.09 %, 89.30 %, compared with the 3-days flexural strength of corresponding SCC. FA series SCC, especially for 50 % FA SCC, have a faster gain rate of the flexural strength than control SCC. At the late curing stage (90 days), utilizing 20 %, 30 %, 40 %, 50 % FA as the alternatives for OPC cause 0.40 %, 0.64 %, 0.88 %, 1.28 % lower flexural strength than SCC with fully cement. In FA series SCC, 50 % FA SCC had a slightly large reduction rate in the 90-days flexural strength, which is below the range of 1.5 %.

### ***Water porosity***

Fig.3 illustrates that the water porosities of SCC samples with 0 %, 20 %, 30 %, 40 %, 50 % FA water-curing for 3, 7, 28, 90 days are in the ranges of 14.72-16.53 %, 13.54-15.11 %, 12.78-14.41 %, 12.14-12.19 %. As expected, at all test periods, the utilization of FA in SCC mixture enhances the water porosity of SCC. After SCC mixtures were stored in water for 3 days, SCC samples with 20 %, 30 %, 40 %, 50 % FA have 4.14 %, 7.74 %, 10.39 %, 12.30 % higher water porosity than SCC prepared with pure cement. The **prolonging** curing period to 90 days, FA series SCC have the **rapider** reduction in the water porosity than reference SCC. At the late curing age (90 days), SCC samples with FA, ranging from 20 % to 40 %, have 0.082 %, 0.16 %, 0.33 % larger water porosity than SCC with fully cement, the presence of high-level FA (50 %) in SCC mixture can no increase anyway the water porosity of SCC. Nagaratnam et al. (2019) proved that the introduction of FA to SCC retards the formation of microstructure at the early stage. The progress in the curing time promotes the secondary hydration reaction of FA, so that the long-term microstructure of FA- blended SCC is more compactness.

## **Water absorption**

The water absorption test of SCC sample was performed at the curing periods of 28, 90 days, and the results are summarized in Fig.4. As shown, at both test ages, the water absorption of SCC with FA at different contents are 4.68 %, 5.11 %, 5.45 %, 6.01 %, 6.72 % and 3.25 %, 3.41 %, 3.56 %, 3.77 %, 4.03 %, the inclusion of FA in SCC results in the larger water absorption than cement-based SCC. At the curing age of 28 days, with the change in the amount of FA from 0 % to 20 %, 30 %, the water absorption of 20 %, 30 % FA SCC mixtures have the increase of 9.19 % 16.45 %, in comparison to control SCC. The content of FA in SCC exceeds 30 %, the high water absorption of SCC was found in SCC mixtures with 40 %, 50 % FA. The water absorption of 50 % FA SCC is more than 6 %, which absorbs about 40-45 % larger water than pure cement SCC. The prolonging curing time is an effective method to lower water absorbed into FA series SCC. After 0 %, 20 %, 30 %, 40 %, 50 % FA-blended SCC were stored in water for 90 days, the water absorption of SCC samples have the reduction of 30.56 %, 33.27 %, 34.68 %, 37.27 %, 40.02 %, compared to the 28-days water absorption of corresponding SCC. FA series SCC exhibit a faster reduction rate in the water absorption than control SCC. A large reduction in the water absorption was found in SCC mixture with high-amount FA (50 %). The prolonging curing period has the positive assistance on the formation of denser microstructure in SCC, and the supply of free water inside hardened SCC becomes slow (Łaźniewska-Piekarczyk 2013).

## **Sorptivity**

Fig.5 shows that, at the curing time of 28 days, the sorptivity of SCC samples with 0 %, 20 %, 30 %, 40 %, 50 % FA are  $9.49 \times 10^{-4} \text{ kg/m}^2 \cdot \text{S}^{0.5}$ ,  $11.76 \times 10^{-4} \text{ kg/m}^2 \cdot \text{S}^{0.5}$ ,  $13.81 \times 10^{-4} \text{ kg/m}^2 \cdot \text{S}^{0.5}$ ,  $15.75 \times 10^{-4} \text{ kg/m}^2 \cdot \text{S}^{0.5}$ ,  $17.30 \times 10^{-4} \text{ kg/m}^2 \cdot \text{S}^{0.5}$ . In comparison to pure-cement SCC, 20 %, 30 % FA incorporating into SCC notable enhance the sorptivity of SCC. The content of FA in SCC is more than 30 %, the increase in the sorptivity of SCC becomes very slowly. It indicates that the sorptivity of SCC depends on the porosity of SCC, the recycle of FA with a low reaction activity in SCC enhances the porosity of SCC, more water were absorbed inside SCC (

Chopra et al. 2015). However, the prolonging curing time improves the long-term sorptivity of series SCC mixtures. During the change in the curing time form 28 days to 90 days, SCC with 0 %, 20 %, 30 %, 40 %, 50 % FA experience the significant reduction in the sorptivity for 19.60 %, 25.76 %, 28.95 %, 30.59 %, 34.10 %. The use of 50 % FA in SCC causes a fastest reduction rate in all series SCC samples. After curing for 90 day, the sorptivity of 0 %, 20 %, 30 %, 40 %, 50 % FA-blended SCC are  $7.63 \times 10^{-4} \text{ kg/m}^2 \cdot \text{S}^{0.5}$ ,  $8.73 \times 10^{-4} \text{ kg/m}^2 \cdot \text{S}^{0.5}$ ,  $9.81 \times 10^{-4} \text{ kg/m}^2 \cdot \text{S}^{0.5}$ ,  $10.93 \times 10^{-4} \text{ kg/m}^2 \cdot \text{S}^{0.5}$ ,  $11.40 \times 10^{-4} \text{ kg/m}^2 \cdot \text{S}^{0.5}$ . The 90-days sorptivity of large-level FA SCC have the slightly differences each other.

## **Carbonation**

The carbonation depth tests of SCC mixtures with FA at different contents were carried out at the exposure times of 3, 7, 14, 28 days, and the results are presented in Fig.6. Fig.6 shows that the evolution rule of the carbonation depth in all SCC mixtures is similar, and can be divided into two stages. At the initial stage of carbonation,  $\text{CO}_2$  in the environment rapidly permeates inside SCC, and SCC had a large carbonation depth. With the progress of carbonation attack, the product of carbonation reaction fills the pore of hardened SCC, which slows the supply of  $\text{CO}_2$  inside SCC. At this exposure stage, the carbonation rate of SCC slowly increases (Philip and De 2014).

Fig.6 also gives that, at the exposure times of 3, 7, 14, 28 days, the carbonation depths of SCC with FA, ranging from 0 % to 50 %, are 0.46-4.57 mm, 0.89-6.39 mm, 1.23-8.25 mm, 1.56-10.98 mm. At the same test period, FA series SCC exhibit lower the resistance against  $\text{CO}_2$  attack than 100 % cement-based SCC, the more FA incorporating into SCC, the larger carbonation depth of SCC. Moreover, for a given SCC mixture, the carbonation rate of SCC mixture was

considered as the proportional to the square-root of the exposure time. Based on the carbonation depth data of SCC at different exposure durations, the carbonation coefficient of SCC were obtained in Fig.7.

As shown in Fig.7 that, the carbonation coefficient of SCC made by fully-cement is  $0.3024 \text{ mm/day}^{0.5}$ . While SCC mixtures with 20 %, 30 %, 40 %, 50 % FA have the higher carbonation coefficient than normal SCC for  $1.0873 \text{ mm/day}^{0.5}$ ,  $1.2938 \text{ mm/day}^{0.5}$ ,  $1.5335 \text{ mm/day}^{0.5}$ ,  $1.7867 \text{ mm/day}^{0.5}$ , the carbonation coefficient of SCC enhance with the change in the content of FA from 20 % to 50 %. SCC with 50 % FA had the largest carbonation coefficient in all SCC mixtures, which is five-six times higher than control SCC. Cengiz (2004) think that the calcium hydroxide (CH) content and the porosity of hardened SCC are two key parameters to control the resistance of SCC against  $\text{CO}_2$  attack. The utilization of more FA in SCC causes the low CH content and the high porosity, it is possible to obtain a fast carbonation rate in high-amount FA SCC.

### ***Chloride ion penetration***

It can be seen from Fig.8 that, regarding SCC mixtures with 0 %, 20 %, 30 %, 40 %, 50 % FA, at test age of 28 days, the total charge passed values of SCC samples within 6 h are 3756.2 C, 3327.4 C, 2752.9 C, 3033.1 C, 3242.7 C, which is recorded in the range from 2000 C to 4000 C, ASTM C1202 specifies as the moderate chloride ion penetrability level. Compared with fully cement-based SCC, FA replaces 20 %, 30 % OPC in SCC, the total charge passed values through SCC exhibit a substantial reduction, the introduction of 30 % FA to SCC has the lowest total charge passed values in all SCC mixtures. The content of FA in SCC mixture is beyond 30 %, the total charge passed values of SCC have a further increase. The total charge passed values of 50 % FA-blended SCC are lower than pure-cement SCC. It indicated that high-amount FA adding into SCC increases the porosity of SCC. However, FA particle has the stronger adsorbing and binding capacity of chloride ion than OPC particle (Yang et al. 2006). Therefore, high-amount (50 %) FA SCC has the relative low chloride ion penetration. The **prolonging** curing period seems beneficial to prevent chloride ion penetration inside FA series SCC. At the curing period of 90 days, SCC samples containing 20 %, 30 %, 40 %, 50 % FA have the total charge passed values over 6 h period for 1685.9 C, 1371.7 C, 1464.2 C, 1535.1 C, the reduction of 27.44 %, 40.97 %, 36.99 %, 33.93 % in the total charge passed values, compared to pure-cement SCC (2323.6 C). The total charge passed values of all FA series SCC curing for 90 days are below 2000 C. The resistance of FA series SCC against the chloride ion penetration changes from the moderate penetrability level of chloride ion (28 days) to the low penetrability level of chloride ion (90 days), according to ASTM C 1202.

### ***Relationships between the water porosity and the compressive strength of SCC***

Fig.9 illustrates that, with regards to SCC mixture curing for 28 days, the water porosity of SCC is closely related to the compressive strength of SCC. In general, irrespective of the content of FA in SCC, SCC with the low water porosity had the large compressive strength of SCC. Between the water porosity (x) and the compressive strength (y) of SCC exist a linear relationship, the fitting formula is  $y = -8.1785x + 170.2625$  with the high correlation coefficient ( $R^2 = 0.9311$ ).

### ***Correlations between the water porosity and the transport property indexes of SCC***

In this study, the correlations between the water porosity and the sorptivity, the total charge passed values through SCC were obtained from the regression analysis. The results are given in Fig. 10-11.

Fig.10 presents that, in case of 28-days FA series SCC, the better linear relationship ( $y = 4.9149x - 53.3939$ ) was observed between the water porosity (x) and the sorptivity (y) of SCC mixture,  $R^2$  is above 0.90. Compared with the correlation between the water porosity and the sorptivity of SCC, it can be found from Fig.11 that the water porosity (x) is less connected with the total charge passed values (y) through SCC ( $y = -332.5x + 7756.4$ ), of which  $R^2$  is  $< 0.50$ .

It is because, the sorptivity of FA SCC mainly relates to the porosity of SCC. While the chloride ion penetration inside FA series SCC not only depends on the porosity of SCC, but also is affected by adsorbing and binding capacity of FA particle for chloride ion (Yerramala and Babu 2011), the combined actions of two factors **decide** the penetration behavior of chloride ion in FA series SCC.

### ***Consumed energy efficiency***

The consumed energy efficiency in the production of SCC is the main indicator to assess the sustainability of SCC. In this study, the statistics on the unit embodied energy of raw materials to prepare SCC derive from reliable available literature (Mithun and Narasimhan 2016; Jones et al. 2011), the consumed energy of SCC in transportation, handling, placement processes were excluded. The consumed energy associated with the production of FA-blended SCC (per  $m^3$ ) were illustrated in Table 5.

As shown in Table 5 that, the consumed energy of SCC mixtures with 0 %, 20 %, 30 %, 40 %, 50 % FA are 2406.252 MJ/ $m^3$ , 1965.756 MJ/ $m^3$ , 1760.412 MJ/ $m^3$ , 1545.132 MJ/ $m^3$ , 1329.852 MJ/ $m^3$ . FA series SCC have the lower consumed energy than SCC without FA. Utilizing FA as the alternatives for OPC in SCC sample reduces the energy consumption, which is beneficial to improve the sustainability of SCC. Among series FA SCC, SCC containing 50 % FA had the lowest consumed energy, the reduction of 44.73 %, in comparison to SCC with 100 % cement.

### ***Environmental efficiency***

The sustainability of SCC also depends on the environmental efficiency, which includes the emissions of greenhouse gas ( $CO_2$ ) and pollutant gases ( $NO_x$ ,  $SO_x$ ) in the production of SCC. The database of national material life cycle assessment centre in China and the literature (CNMLCA 2010; Yang et al. 2014) provide the different gas emission factors (in kg/kg) of individual ingredient to prepare SCC, the emission data were summarized in Table 6. The emissions of  $CO_2$ ,  $NO_x$ ,  $SO_x$  in the preparation of SCC with FA at different contents are showed in Fig.12.

Fig.12 indicates that the emitted amounts of  $CO_2$ ,  $NO_x$ ,  $SO_x$  gases in the manufacture of SCC mixtures with 0 %, 20 %, 30 %, 40 %, 50 % FA are 415.326-243.285 kg/ $m^3$ , 0.856-0.444 kg/ $m^3$ , 0.493-0.253 kg/ $m^3$ . Among the environmental efficiency, the largest environmental load in the production of SCC was  $CO_2$  emission. When OPC of 20-50 % in SCC was replaced by FA, the emissions of  $CO_2$  reduce about 19.17 %, 28.75 %, 38.34 %, 41.42 %, in comparison to cement-based SCC. The release of  $NO_x$  gas is the second environmental load in the preparing process of SCC. FA as the substitutes for cement decreases the emission of  $NO_x$  gas in SCC, the emission amounts of  $NO_x$  gas in the preparing of 20 %, 30 %, 40 %, 50 % FA-blended SCC are 80.72 %, 71.14 %, 61.45 %, 51.87 % of pure-cement SCC. Poisonous  $SO_x$  gas also produces some negative effect on the environment. Compared with control SCC, SCC with 20 % FA has the reduction of 19.47 % in the emissions of  $SO_x$ , the highest reduction rate (48.68 %) in the emission amounts of  $SO_x$  was found in 50 % FA SCC.

## **Conclusions**

Nowadays, the utilization of large amount industrial by-product FA as the substitutes for cement in SCC is a promising option to reduce the negative effect of SCC industry on the environment. In this study, FA was used to replace cement in SCC at five levels (0 %, 20 %, 30 %, 40 %, 50 %). The mechanical properties, the water porosity, the transport behaviors and the sustainability of SCC were assessed. The following conclusions were drawn:

- At the **initial** curing stage (3 days), the inclusion of FA in SCC mixture lowers the mechanical behaviors and increases the water porosity. After two series SCC mixtures were water-cured for 28 days, FA series SCC have higher the water absorption, the sorptivity, the carbonation depth, the carbonation coefficient than pure-cement SCC. Utilizing FA in SCC is an effective method to resist against the penetration of chloride ion into hardened
- The **prolonging** curing time was beneficial to improve the long-term behaviors of FA-blended SCC. At the late curing period (90 days), 20 %, 30 %, 40 % FA were employed as the alternatives for cement to prepare SCC. The compressive strength, the flexural strength and the water porosity of SCC sample have the reduction of 0.46-2.09 %, 0.44-1.28 % and the increase of 0.82-0.41 %, in comparison to control SCC. Beyond the certain content of FA (40 %), the slightly lower mechanical properties and the higher water porosity than cement-based SCC can be achieved by utilizing 50 % FA in SCC. The **difference** in the mechanical properties and the water porosity between normal cement SCC and 50 % FA SCC is below the range of 2.5 %. With the progress in the curing period, the water absorption and the sorptivity of SCC mixtures with FA have the faster reduction rate than SCC with fully cement. At the test age of 90 days, the resistance of FA series SCC mixtures against the chloride ion penetration enhances from the moderate penetrability level of chloride ion (28 days) to the low penetrability level of chloride ion (90 days), classified by ASTM C 1202.
- In case of FA series SCC water-curing for 28 days, there are the better linear relation between the water porosity and the compressive strength. Among the transport property indexes of SCC, the relationship between the water porosity and the sorptivity are superior to the correlation between the water porosity and the total charge passed values through SCC.
- In the production of SCC, the recycle of FA to SCC causes the reduction of 18.31-44.73 % in the consumed energy. The released amounts of CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub> from FA series SCC are 19.17- 41.42 %, 19.28-48.13 %, 19.47-48.68 % lower than SCC made with fully cement. The lowest energy **consumption** and emitted amounts of CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub> were found in the manufacture of SCC with 50 % FA.
- The application of large-amount FA in SCC mixture has the positive contribution to the long -term behaviors, the consumed energy efficiency and the environmental efficiency of SCC. 50 % FA SCC curing for long time was considered as the sustainable concrete

## Declarations

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**Authors' contributions:** Hui Zhao: Investigation, Methodology, Software, Writing-Reviewing and Editing. **Wei Sun:** Original draft preparation, Conceptualization. Xiaoming Wu: Original draft preparation, Conceptualization. **Bo Gao:** Original draft preparation, Conceptualization.

### Compliance with ethical standards

**Conflict of interest:** The author declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

**Ethical approval:** This article does not contain any studies with human participants or animals performed by any of the authors.

**Consent to participate:** Not applicable

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## Tables

**Table 1.** The oxide compositions, the mineral compositions and the physical properties of OPC, FA

Oxide compositions (%)								Mineral compositions (%)				
Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	CaO	Fe <sub>2</sub> O <sub>3</sub>	MgO	SO <sub>3</sub>	K <sub>2</sub> O	Na <sub>2</sub> O <sub>eq</sub>	C <sub>3</sub> S	C <sub>2</sub> S	C <sub>3</sub> A	C <sub>4</sub> AF
Cement (OPC)	21.35	4.94	60.16	2.71	0.46	1.96	0.48	1.00	60.74	16.18	6.66	14.17
Fly ash (FA)	56.79	28.21	< 3	5.31	5.21	0.68	1.34	0.45	-	-	-	-
Physical properties												
Sample	Specific gravity (g/cm <sup>3</sup> )	Blaine fineness (cm <sup>2</sup> /g)	Compressive strength (MPa)			Flexural strength (MPa)						
			3d	7d	28d	3d	7d	28d				
Cement (OPC)	3.16	3519	30.0	45.6	60.2	5.8	7.4	8.3				
Fly ash (FA)	2.31	3960	-	-	-	-	-	-				

Abbreviations: Na<sub>2</sub>O<sub>eq</sub> = Na<sub>2</sub>O + 0.658K<sub>2</sub>O

**Table 2.** The particle gradations, the physical properties of fine aggregate and coarse aggregate

Sieve size (mm)	Cumulative pass amount (%)	
	Fine aggregate	Coarse aggregate
25	-	100
20	-	75.76
15	-	42.3
10	-	5.26
5	100	0.6
4.75	95.4	-
2.36	82.8	-
1.18	72.2	-
0.6	52.2	-
03	31	-
0.15	3.2	-
Fineness modulus	2.46	-
Physical properties		
Density-OD (kg/m <sup>3</sup> ) <sub>eq</sub>	2580	1635
Density-SSD (kg/m <sup>3</sup> ) <sub>eq</sub>	2620	1680
Water absorption (%)	0.80	1.2

Abbreviations: OD-Density at absolutely dry condition, SSD-Density at saturated surface dry condition

**Table 3.** The mix proportions of series SCC mixtures

Mix	W/B	Binder materials (kg/m <sup>3</sup> )		Fine aggregate (kg/m <sup>3</sup> )	Coarse aggregate (kg/m <sup>3</sup> )	PCA SP (kg/m <sup>3</sup> )
		OPC	FA			
OPC100	0.35	460	0	693.81	1085.2	1.104
OPC80FA20	0.35	368	92	693.81	1085.2	1.104
OPC70FA30	0.35	322	138	693.81	1085.2	1.104
OPC60FA40	0.35	276	184	693.81	1085.2	1.104
OPC50FA50	0.35	230	230	693.81	1085.2	1.104

**Table 4.** The rheological properties of series SCC mixtures

Mix	Slump flow (mm)					Slump flow loss rate (2 h) (%)	L-box test		GTM segregation ratio (%)
	0 h	0.5 h	1h	1.5 h	2 h		H <sub>2</sub> /H <sub>1</sub> ratio (%)	Time (s)	
OPC100	695	554	486	454	420	39.57	0.93	18.9	9.2
OPC80FA20	724	646	605	574	549	24.17	0.95	18.5	9.4
OPC70FA30	746	676	641	616	598	19.84	0.97	18.2	9.7
OPC60FA40	759	706	674	652	640	15.68	0.98	17.9	9.8
OPC50FA50	775	723	705	687	663	14.45	0.99	17.3	9.9

**Table 5.** The consumed energy values of series SCC mixtures in the production (per m<sup>3</sup>)

Raw materials	Embodied energy (MJ/kg)	Mix no				
		OPC100	OPC80FA20	OPC70FA30	OPC60FA40	OPC50FA50
OPC (kg)	4.80	2208.0	1766.4	1545.6	1324.8	1104
FA (kg)	0.12	0	1.104	16.56	22.08	27.6
Fine aggregate (kg)	0.08	56.19861	56.19861	56.19861	56.19861	56.19861
Coarse aggregate (kg)	0.08	90.0716	90.0716	90.0716	90.0716	90.0716
PCA SP (kg)	16.46	18.17184	18.17184	18.17184	18.17184	18.17184
Water (kg)	0.21	33.81	33.81	33.81	33.81	33.81
Total consumed energy (MJ/m <sup>3</sup> )	-	2406.252	1965.756	1760.412	1545.132	1329.852

**Table 6.** The unit emission values of CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub> in the production of raw materials to prepare SCC mixture

Raw materials	Functional unit	Output ingredients (kg)		
		CO <sub>2</sub>	NO <sub>x</sub>	SO <sub>x</sub>
OPC	kg	0.885	1.79 × 10 <sup>-3</sup>	1.05 × 10 <sup>-3</sup>
FA	kg	1.96 × 10 <sup>-2</sup>	1.02 × 10 <sup>-6</sup>	8.36 × 10 <sup>-6</sup>
Fine aggregate	kg	2.34 × 10 <sup>-3</sup>	1.52 × 10 <sup>-5</sup>	9.49 × 10 <sup>-6</sup>
Coarse aggregate	kg	5.71 × 10 <sup>-3</sup>	2.00 × 10 <sup>-5</sup>	3.00 × 10 <sup>-6</sup>
PCA SP	kg	0.34	-	-
Water	kg	1.96 × 10 <sup>-4</sup>	-	-

# Figures

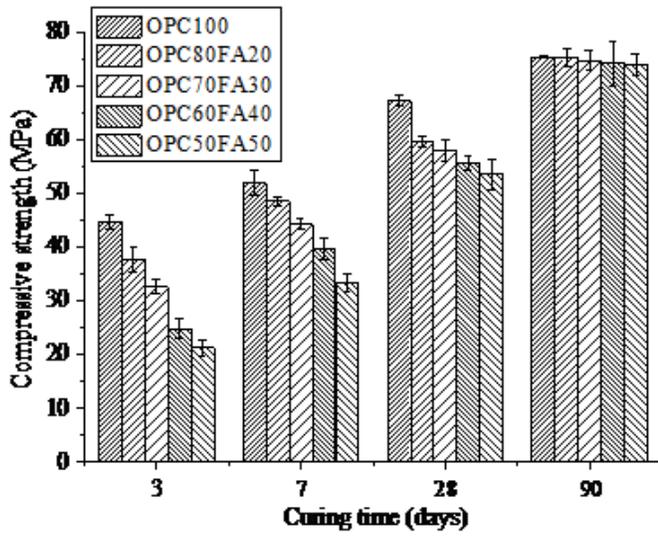


Figure 1

The compressive strength of series SCC mixtures at different curing periods

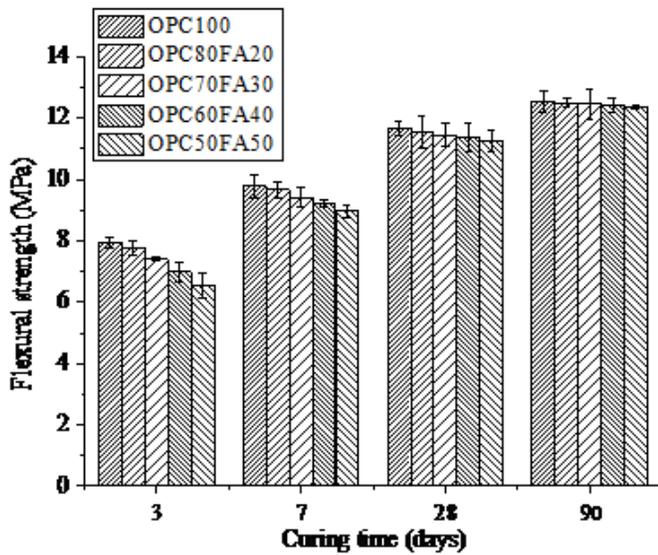


Figure 2

The flexural strength of series SCC mixtures at different curing periods

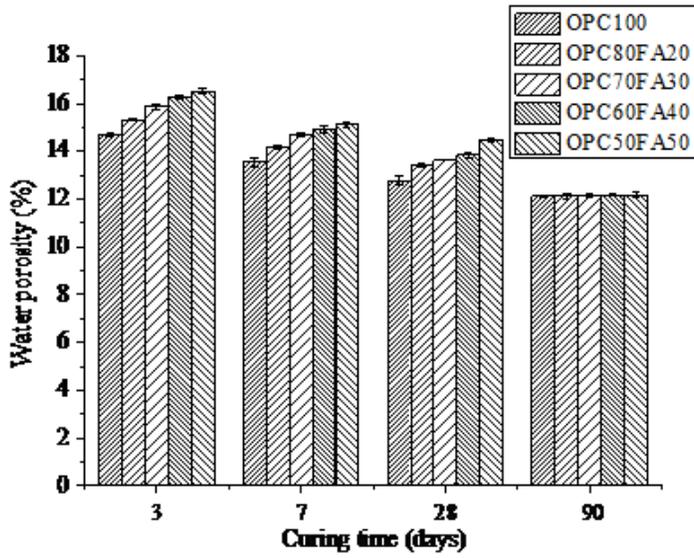


Figure 3

The water porosities of series SCC mixtures at different curing periods

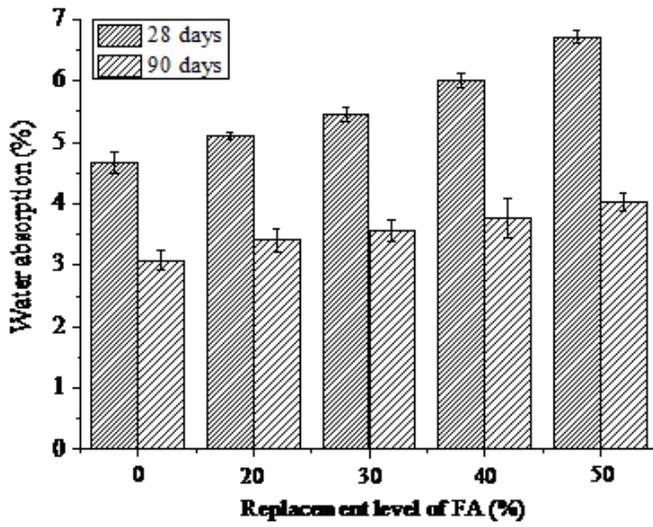


Figure 4

The water absorption of series SCC mixtures at both curing periods

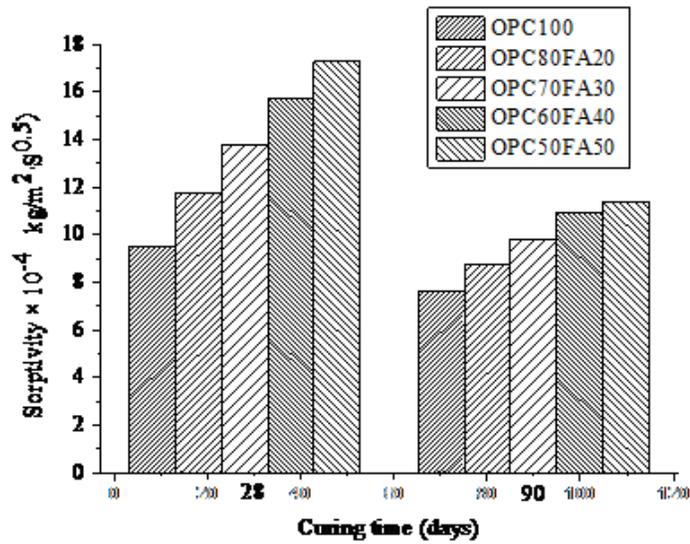


Figure 5

The sorptivity of series SCC mixtures at both curing periods

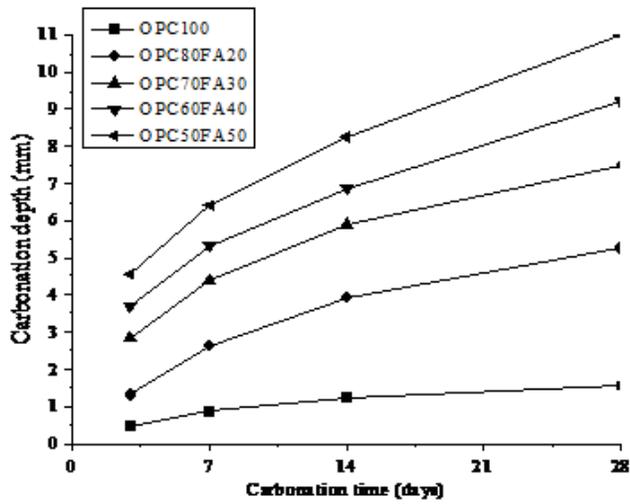


Figure 6

The carbonation depths of series SCC mixtures at different exposure durations

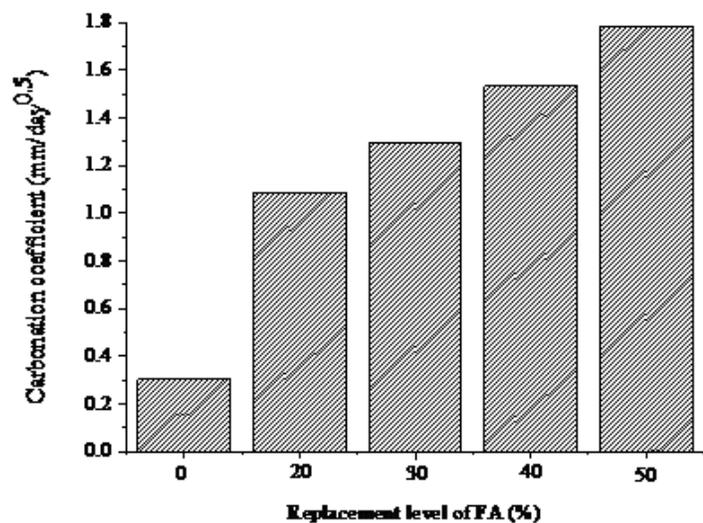


Figure 7

The carbonation coefficient of series SCC mixtures

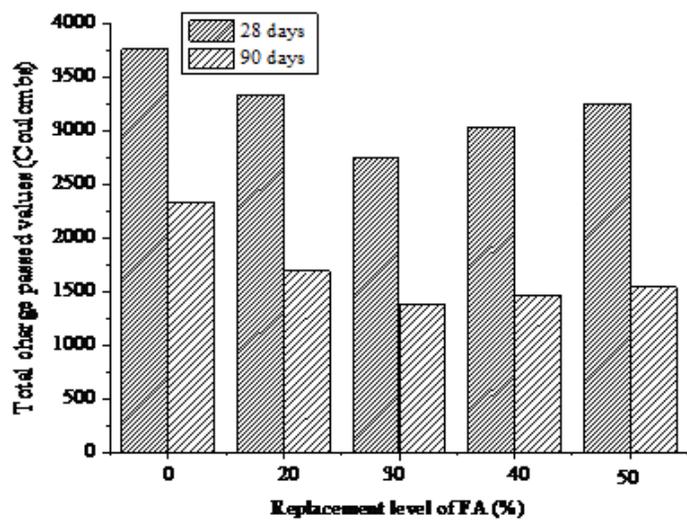
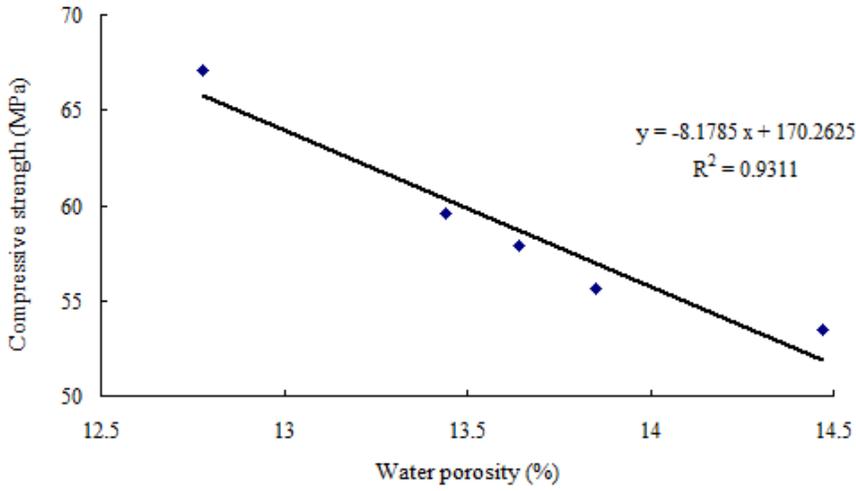


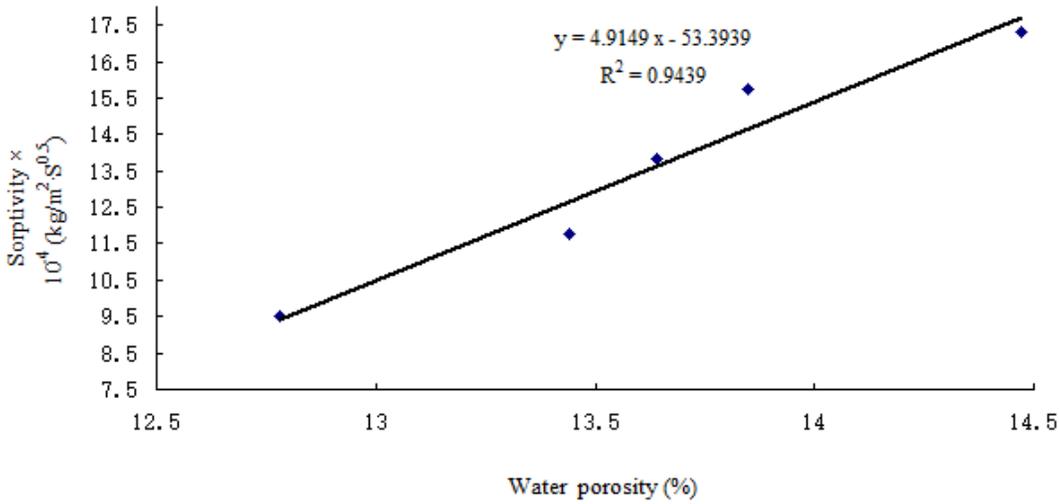
Figure 8

The total charge passed values of series SCC mixtures at both curing periods



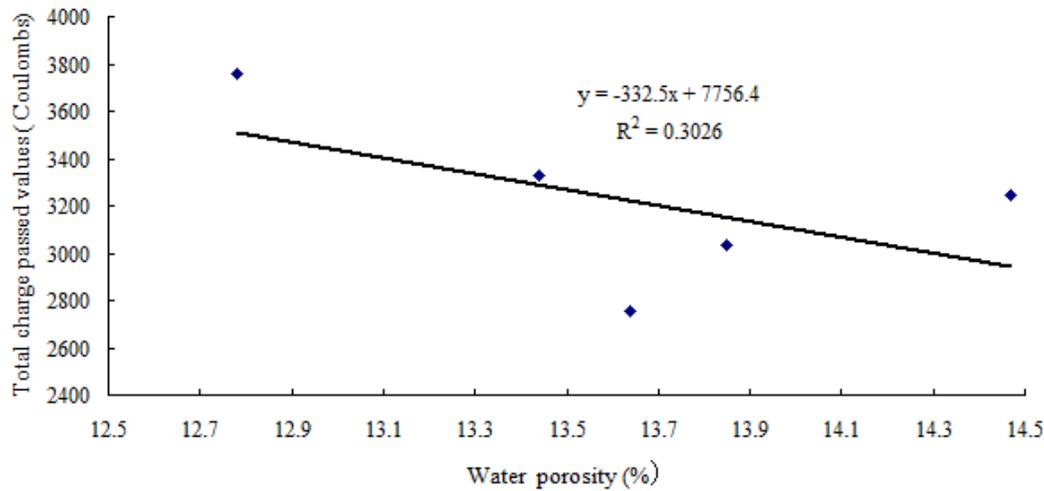
**Figure 9**

The relationship between the water porosity and the compressive strength of SCC at the curing period of 28 days



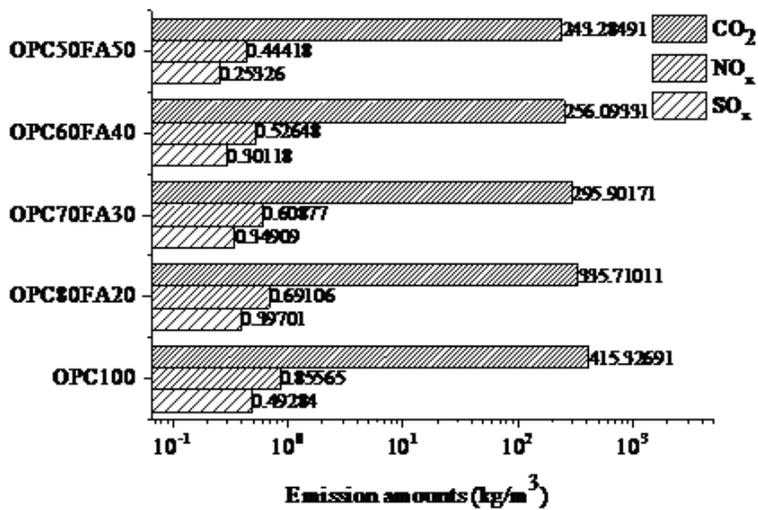
**Figure 10**

The relationship between the water porosity and the sorptivity of SCC at the curing period of 28 days



**Figure 11**

The relationship between the water porosity and the total charge passed values of SCC at the curing period of 28 days



**Figure 12**

The released amounts of CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub> for series SCC mixtures