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Sorptivity of self-compacting concrete containing fly ash and silica fume

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HIGHLIGHTS

- Sorptivity decreased with partial replacement of cement by FA and SF in SCC.
- An increased 28-day compressive strength of SCC was obtained by a combined use of FA and SF while it generally decreased with only FA replacement.
- No obvious correlation achieved between sorptivity and compressive strength.

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ABSTRACT

This paper presents the surface water absorption of self-compacting concrete (SCC) containing fly ash and silica fume using sorptivity test. Ordinary Portland cement was partially replaced by various combinations of fly ash and silica fume. Test results show that the presence of fly ash and silica fume significantly reduce the surface water absorption of self-compacting concrete at a water-binder ratio of 0.38. When only fly ash is used to partially replace Ordinary Portland cement, a more noticeable reduction in sorptivity is found when the fly ash content is greater than 20%. The effect of combined use of fly ash and silica fume on reducing the water absorption and sorptivity is much more significant than using fly ash only. Moreover, it is noted that increasing the proportion of fly ash and silica fume leads to an enhanced reduction in water absorption. The addition of fly ash and silica fume, in general, increases the 28-day cube strength. However, there is no correlation between the compressive strength and the sorptivity in SCC achieved.

1. Introduction

It is necessary for reinforced concrete (RC) structures to undertake maintenance over its design and service life. However, the frequency of maintenance works can be minimized using a durable concrete material. In RC structures, corrosion subsequently leads to deterioration in structural capacity, serviceability and even the appearance of the structure. It is apparent that air and water play an important role in triggering the corrosion process. If the ingress of these two components can be hindered, the occurrence of corrosion would be prevented. One of the methods to measure the ingress of water into concrete is by sorptivity test. This test is used to determine the properties of the near surface concrete which can control the transport of water into the concrete and to the reinforcement. The water absorption or sorptivity of concrete can be regarded as a measure of the capillary forces as exerted by the pore structure causing the liquids to be drawn into the concrete [1]. However, the sorptivity test is only applied to the surface of the concrete, not much information about the bulk properties of concrete can be derived. It has been reported that the sorptivity of concrete was affected by its surface condition. Besides, the initial moisture content of concrete also altered the additional absorption of water [2]. Tasdemir [3] conducted a series of sorptivity tests on Ordinary Portland Cement (OPC) concrete with sand instead of cement being partially replaced by mineral admixtures including fly ash (FA), limestone, sandstone and silica fume (SF) and the test results revealed the sorptivity coefficient decreased as the compressive strength of concrete increased and the sorptivity coefficient was almost constant for water-cured concretes. Abdul Razak et al. [4] investigated the initial surface absorption, water absorption and sorptivity of concrete containing metakaolin (MK) and SF, each 10%. The results showed that the presence of MK and SF greatly reduced the initial surface absorption, water absorption and sorptivity of concrete as compared to OPC concrete. Experimental results of Guneyisi et al. [5] indicated that the effect

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of MK and SF on mechanical, permeability and shrinkage properties of concrete with water binder ratio of 0.25 and 0.35 was significant. The 28-day compressive strength for MK and SF concretes were higher than the control concretes and the sorptivity coefficients decreased with the introduction of MK and SF. An inverse proportionality between sorptivity values and mechanical properties was highlighted, i.e. concrete with the lowest sorptivities had the highest compressive strengths, especially for those having 15% MK or SF. Chen et al. [6] investigated limestone fines as cement paste replacement and the limestone significantly enhanced the strength of concrete.

In the recent decade, self-compacting concrete (SCC) has been characterized as a promising construction material. This is attributed to the fact that SCC is able to be placed and compacted under its own weight with no vibration needed which is extremely important especially in areas with highly congested reinforcement. With the use of SCC, it is believed that the chance of having corrosion in RC structures is lowered and the possibility of poor workmanship which may lead to honeycombing and segregation can be eliminated [7]. As a result, SCC has to be cohesive at the same time no segregation or bleeding of fresh concrete is anticipated. To achieve such effect, a SCC mix is usually consisted of superplasticizer (SP) and viscosity modifying agent (VMA), along with high content of fines. Regarding the substitute of fine content, FA which enhances the workability and reduces the cracking due to lower heat of hydration has been introduced in SCC so that the dosage of SP can be reduced while maintaining the required slump flow. Apart from FA, SF could enhance the bond between paste and aggregate through its pozzolanic reaction appears to be a good substitute in fine content. In a recent research, SCC incorporating MK [8] was also investigated.

Khatib [9] studied SCCs containing FA by 0–80% cement replacement at a water-binder ratio of 0.36. According to the test results, a systematic increase in water absorption with increasing FA content was found for SCCs with 1, 28 and 56 days of curing. However there was a decrease in compressive strength with increased FA content. An inverse relationship between strength and water absorption was therefore suggested. Kanellopoulos et al. [10] also observed similar variations between the compressive strength and sorptivity. The same variation between compressive strength and sorptivity was noted. Dinakar et al. [11] conducted durability tests which include water absorption test, on SCCs with FA percentage from 0% to 85%. Higher water absorption in FA SCCs than normal concretes at the same strengths was concluded. Wongkeo et al. [12] examined the compressive strength and water absorption of SCC with a high volume of FA and SF. According to their experimental results, water absorption of SCC containing FA was greater than control concrete, however this decreased with increasing SF content. In terms of compressive strength, SCC showed decreased strength with increasing FA content, even lower than the control concrete. Addition of SF in the SCC mix gave higher strengths. Mohamed [13] studied the compressive strength of three different SCC mixes consisted of FA, SF and a combination of FA and SF. A water-cement (W/C) ratio of 0.42 and the cement contents of 450 kg/m^3 and 550 kg/m^3 were adopted in the SCC mixes. The experimental results on 450 cylinders revealed an optimum compressive strength for SCC with 15% cement replacement by SF and SCC with 30% cement replacement by FA. The 28-day compressive strength for SCC with 15% SF was higher than those with 30% FA. The results also indicated that 10% of SF and 10% of FA was the best percentage combination in the adopted SCC mixes. In addition, water cured specimens generally gave higher compressive strength.

Hassin et al. [8] conducted tests on twelve SCC mixtures with different proportions of metakaolin (MK) and SF in which the water-binder ratio of 0.4, binder content of 450 kg/m^3, a maximum of 11% SF by cement replacement and varied amount of high range water reducer were used to meet the required slump flow of 650 mm. Based on the results of some mechanical and durability tests, they concluded that the 28-day compressive strength of SCC increased with both MK and SF contents. An optimum percentage of SCC containing SF was found to be at 8%. Different permeation properties of SCC were also studied by Zhu and Bartos [14]. Experimental tests on SCC at strengths between 40 MPa and 60 MPa with the addition of powder (limestone, pulverized fuel ash) as filler were carried out and the results revealed that the water absorption of SCC was significantly lower than that of normally vibrated concrete.

2. Research significance

A more extensive use of SCC in the construction industry can only be achieved when more durability data regarding SCC containing different ingredients is available. Sorptivity as one of the main durability considerations requires more study. As the study on sorptivity of SCC in the literature is relatively limited, this paper attempts to present some sorptivity test data on SCC containing different volumes of FA and SF by partial replacement of OPC. Since the data were obtained from standard sorptivity test, future research results can be compared directly with the current data. In addition to sorptivity, the compressive strength of SCC under the effect of cement replacement by FA and SF is also investigated. It is of particular importance for practising concrete and construction professional to understand the correlation between sorptivity and compressive strength of SCC.

3. Experimental program

3.1. Materials

In this study, OPC was used as a main binder while FA and SF was employed as mineral admixtures. The OPC used is complied with BS12:1991 [15]. The type of FA used in the study is Class F in accordance with the ASTM C 618-99 [16] and the SF is complied with ASTM C 1240-99 [17]. Typical particle size of FA is below 20 μm while SF has an average diameter of about 0.1 μm. River sand and crushed granite with a maximum size of 10 mm were used as fine and coarse aggregate respectively. They are all complied with BS882:1992 [18]. A carboxylate polymer based clear liquid SP and a liquid polymer-based VMA complying with BS 5075: Part 3:1985 [19] was introduced as chemical admixtures.

3.2. Mix proportioning

Two series (F and FS) of concrete mixes were prepared. The detailed mix proportions are presented in Table 1.

The F-series aims to compare the sorptivity of SCC containing different amounts of FA. The replacement levels (by weight) of OPC by FA were 0% (control), 12.9%, 20%, 30%, 40% and 50%. The FS-series attempts to investigate the combined effect of FA and SF on the SCC's sorptivity. Class F FA is normally used at a dosage of 15–25% by mass of cementitious materials, thus the amount of FA was maintained at 25% of OPC while the SF levels were 0%, 5%, 10% and 15%. Therefore the total OPC replacement levels by FA and SF were 25%, 30%, 35% and 40%. The water-binder (W/B) ratio was 0.38 (binders here included OPC, FA and SF) and a water content of 235.6 kg/m^3 was adopted. The fine and coarse aggregate contents were 780 kg/m^3 and 720 kg/m^3 respectively for all SCC mixes. In each SCC mix, two specimens were cast for subsequent tests.

In order to satisfy the requirements of SCC, SP and VMA were added. It is noteworthy that all SCC mixes in this study were produced using single type of SP and VMA although the effect of types of SP and VMA on the properties of SCC has been reported elsewhere [20–21]. The proportions of SP and VMA were determined according to the test results of slump flow, U-box [22] and segregation [23]. Essentially, the following requirements were to be fulfilled.

- a minimum flow diameter of 650 mm
- a height difference of less than 30 mm in the U-box test
- a segregation index of less than 20%

Table 1
Mix proportions of concrete.

Mixture	W/B	Water	Unit weight (kg/m^3)					Quantity (l/m^3)	
			Binder			Fine aggregate	Coarse aggregate	SP	VMA
			OPC	SF	FA				
F1 (control)	0.38	235.6	620	0	0	780	720	4.44	3.80
F2	0.38	235.6	540	0	80	780	720	3.03	3.40
F3	0.38	235.6	496	0	124	780	720	4.00	9.27
F4	0.38	235.6	434	0	186	780	720	4.00	12.67
F5	0.38	235.6	372	0	248	780	720	3.77	13.00
F6	0.38	235.6	310	0	310	780	720	3.35	12.00
FS1	0.38	235.6	465	0	155	780	720	2.77	10.00
FS2	0.38	235.6	434	31	155	780	720	2.73	7.87
FS3	0.38	235.6	403	62	155	780	720	2.83	13.40
FS4	0.38	235.6	372	93	155	780	720	4.10	14.33

3.3. Mixing and placing

A rotary type pan mixer of volume 0.5 m^3 was used to mix the concrete. At the outset, the coarse aggregate, fine aggregate, OPC, SF and FA were dry mixed for 2 min. Subsequently, the water was thoroughly mixed with SP, before pouring to the concrete mix. VMA was also added and mixed for 3 min. Manual mixing was followed to check the uniformity and then allowed to mix for 3 more minutes. Similar mixing procedures were suggested elsewhere [24]. After mixing, slump flow, U-box and segregation tests were conducted. The concrete was then placed in the steel fabricated 100 mm cube molds kept on a vibrating table. A steel trowel was used to finish the fresh concrete surface.

3.4. Specimen preparation

All concrete specimens were demolded after 24 h and were kept in a water curing tank. Two days before testing, the specimens were removed from the curing tank and were dried in an oven (at 105 °C) for 24 h. After that, the specimens were stored inside desiccators (Fig. 1) for a further 24 h. At 28 days, the sorptivity test was carried out. It was pointed out that the sorptivity of concrete measured at 28 days was quite an exact approximation of further measured values [25]. In addition, 28-day cube compressive strength was also obtained by compressive loading tests on a compression testing machine.

3.5. Test methods

Before the sorptivity test was carried out, the weight and the cross-sectional area of all concrete specimens were measured. A steel tray of water (at 20 °C) to a depth of 2 mm was held level to the ground. Specimens were then placed over two glass rods (~1 mm dia.) inside the tray to allow free water movement (Fig. 2). After a time interval of 5, 10, 30, 60 and 120 min, specimens were removed from the tray and the weights were recorded. During the test, water was re-filled into the tray to maintain a water depth of 2 mm. The sorptivity coefficient, *S*, was then calculated by the following equation.

$$i = S \times \sqrt{t} \quad (1)$$

where i (g/mm^2) represents the cumulative amount of water absorbed per unit cross-sectional area of concrete specimen, S ($g/mm^2/min^{1/2}$) is the sorptivity coefficient and t denotes the time measured in minutes.

4. Results and discussions

4.1. Sorptivity

The cumulative amount of water absorbed per unit cross sectional area is presented in Table 2. Apparently, all SCC mixes show an increase in water absorbed along with the measured times. It is also found that the F1 (control) gives almost the highest amount of water absorbed.

The influence of FA content on the water absorbed per unit area of concrete is depicted in Fig. 3. It is shown that the presence of FA in all SCC mixes gives rise to reduced water absorbed per unit area. When the percentage replacement of OPC by FA increases from 0% to 50%, the reduction in water absorbed becomes more significant. It is also indicated that addition of FA in SCCs slightly reduces the water absorption at initial stage, this reduction amplifies along with time. This is attributed to the fact that FA particles fill up the micro air voids inside the concrete matrix and thus inhibit

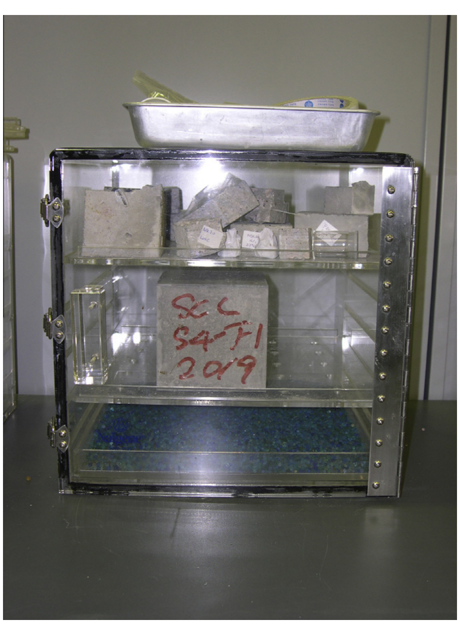

Fig. 1. Concrete specimens in desiccator.

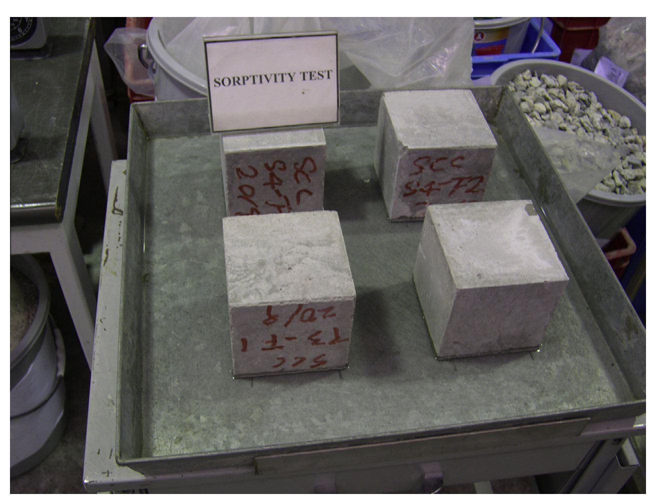

Fig. 2. Sorptivity test.

Table 2
Surface water absorption results.

Mixture	% replacement of OPC by FA	% replacement of OPC by (FA + SF)	i (10^{-4} g/mm^2) at various times (min)				
			5	10	30	60	120
F1 (control)	–	–	2.81	3.99	6.58	9.13	12.08
F2	12.9	–	2.36	3.50	6.18	8.43	11.00
F3	20	–	3.34	4.34	6.32	8.20	10.17
F4	30	–	2.45	3.39	5.25	7.04	8.78
F5	40	–	1.83	2.79	4.25	5.59	7.11
F6	50	–	1.10	1.73	2.92	3.90	5.18
FS1	–	25	1.99	2.75	4.56	5.83	7.06
FS2	–	30	1.83	2.55	4.07	5.10	6.14
FS3	–	35	1.75	2.38	3.24	4.21	5.17
FS4	–	40	1.51	2.09	3.13	4.13	4.90

the water absorption. A similar trend for FS-series SCC mixes is also observed where the presence of both SF and FA in SCCs leads to a slightly enhanced reduction in water absorption. However, when the percentage replacement of OPC by (FA + SF) is greater than 35%, the reduction in water absorption appears to be insignificant. Furthermore, when the results of cumulative weight of water absorbed in F5 and FS4 are compared, SF gives a greater effect on reduction of water absorption than FA. Similar results were found by other researchers [9,12]. This phenomenon is due to the fact that FA particles are larger than SF particles. The filler effect of FA may not be salient as compared to SF. Moreover, the pozzolanic reaction by SF enhances the homogeneity of the SCC structure thus resulting in reduced sorptivity.

In Fig. 3, it also shows that there is an average reduction of 20.3% in water absorbed for all measured times when the percentage replacement of OPC by FA is increased from 30% to 40% (by comparing F4 and F5). However, when the results of F4 and FS2 (both 30% replacement) are investigated, the effect of SF on reducing the water absorbed is more noticeable and the reduction of water absorbed increases to 24.4%. A slightly further reduction of 25.2% is indicated from the results of F5 and FS4 (both 40% replacement). This further indicates that SF is more effective in reducing water absorption in SCC. A similar behavior was reported by Guneyisi et al. [5].

Sorptivity test measures the rate of penetration of water into the concrete pores by capillary suction. In order to calculate the sorptivity coefficient (S), the cumulative amount of water absorbed per cross sectional area (i) was plotted against the square root of time $\sqrt{t}$, then a best fit line was obtained by regression analysis and then S was determined from the gradient of the best fit straight line. The water absorbed per unit area is plotted against the square root of time in Figs. 4 and 5.

The obtained sorptivity coefficients are tabulated in Table 3. Apart from the control specimen (F1) which gives the highest sorptivity, presence of FA and SF reduces the sorptivity value, the decrease in sorptivity can be greater than 50% when more than 40% OPC is replaced by FA and SF. It can also be seen that a more noticeable reduction in sorptivity occurs when the FA content is greater than 20%. Similar results were reported by Sariciment et al. [26] and Chan and Ji [27] for pulverized fly ash concrete. It is observed that, at the same OPC replacement level, F4 gives 31.8% reduction in sorptivity while FS2 shows 54.2% decrease. When the results of F5 and FS4 are compared, the reduction in sorptivity coefficient increases from 44.9% to 63.6%. This indicates that SCCs with addition of FA and SF gives a higher decrease in sorptivity coefficient than FA SCCs. It is concluded that the presence of SF in SCCs provides a more prominent effect in reducing the sorptivity and the water absorption.

4.2. Compressive strength

The results of 28-day cube compressive strength are shown in Table 3. Replacement of 12.9% OPC by FA enhances the 28-day compressive strength of hardened SCC, but further increase in FA

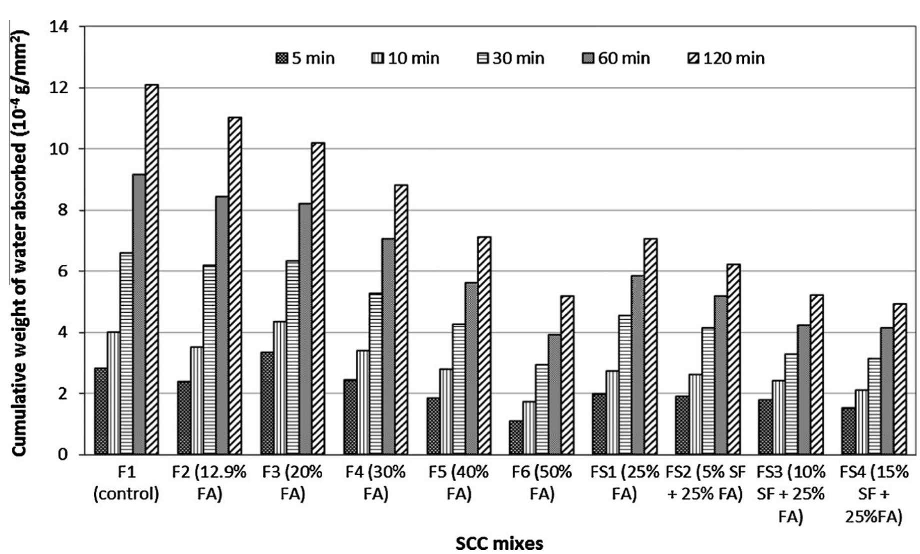

Fig. 3. Surface water absorption results.

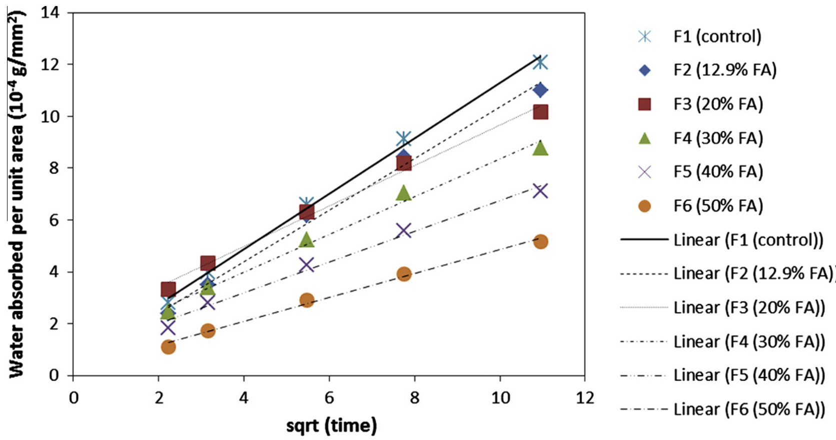

Fig. 4. Surface water absorption against time$^{1/2}$ for F-series specimens.

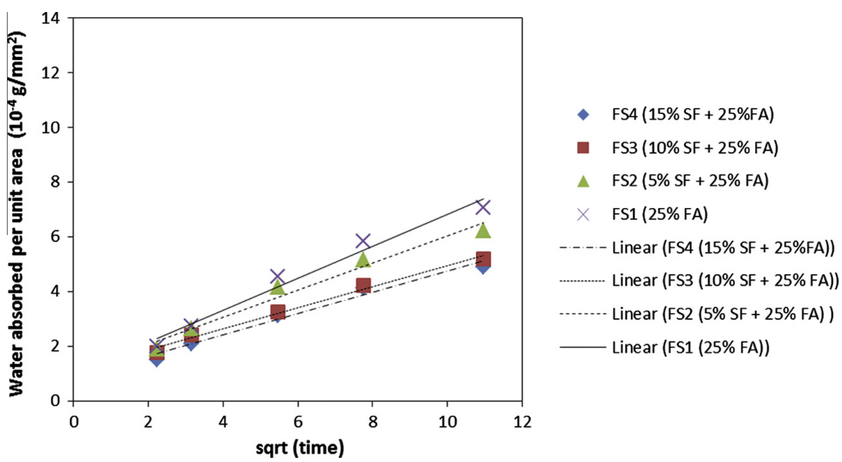

Fig. 5. Surface water absorption against time$^{1/2}$ for FS-series specimens.

Table 3
Sorptivity coefficient and 28-day cube strength results.

Mixture	Sorptivity coefficient (10^{-4} g/mm^2/min$^{1/2}$)	28-Day cube strength (MPa)
F1 (control)	1.07	57.68
F2	0.99	61.00
F3	0.78	54.38
F4	0.73	52.60
F5	0.59	44.75
F6	0.46	38.12
FS1	0.59	58.98
FS2	0.49	64.84
FS3	0.39	74.55
FS4	0.39	69.08

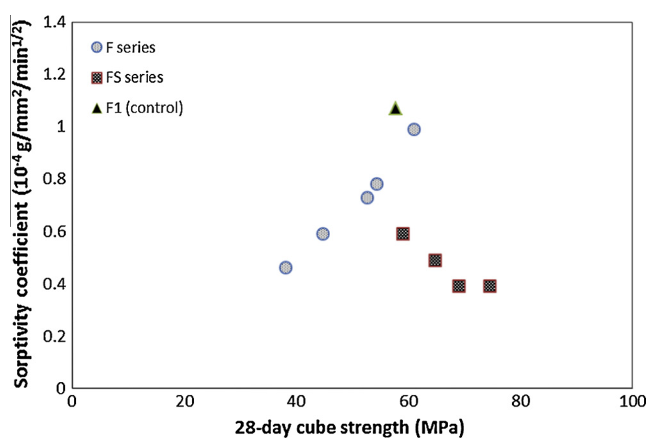

Fig. 6. Sorptivity coefficient against 28-day cube strength.

content leads to a reduction in compressive strength. On the contrary, addition of SF generally increases the concrete strength. This reduced strength for FA concrete and the enhanced strength for SF concrete were also reported by other researchers [3,8,11]. Since the average particle size of FA is higher than that of SF, the pores in the paste and interfaces are not completely filled, therefore excessive use of FA leads to a lowered strength. However, the strength development in FS series is again due to the pozzolanic reaction.

In contrast with the suggested combination of 10% FA and 10% SF for the highest compressive strength [13], the current results indicate a maximum 28-day cube strength of 74.55 MPa is obtained when 25% FA and 10% SF are adopted in the SCC mix. This further proves that an enhanced compressive strength of SCC can be resulted by a combined use of FA and SF.

4.3. Correlation

The sorptivity coefficients and 28-day cube compressive strength are plotted in Fig. 6. It is apparent that both F-series and

FS-series SCCs give a lower sorptivity than the control SCC. The F-series SCC shows lower 28-day cube strength than the control whereas the FS-series SCC gives higher strength values. The increasing trend of compressive strength with the sorptivity for SCC with addition of FA was also reported by some researchers [3,9]. However, the trend is reversed when SF is added to the current SCC mixes. It is thus unable to conclude a definite correlation between sorptivity and 28-day cube strength. This finding is in contrast with other research work [10]. Depending on the proportion of mineral admixtures in the SCC mix and other environmental factors (such as curing method [13]), different sorptivities and 28-day compressive strengths can be achieved. In SCC mixes, the 28-day cube strength as a single indicator for estimation of sorptivity can be erratic.

It is generally accepted that the compressive strength of concrete increases with addition of SF and FA, especially in binary mixes with OPC. During the cement hydration process, if the excess calcium hydroxide produced reacts with just enough pozzolans to form calcium silicate hydrate (CSH), this minimum amount of pozzolans is deemed to be an optimum. The calcium hydroxide formed the interfacial transition zone around aggregates reduces the bond strength between aggregate and cement paste. Therefore, elimination of calcium hydroxide by formation of additional CSH increases the binder amount and thus enhanced compressive strength. Results in the literature show an optimum binary mix of around 25–30% FA or 10–15% SF leads to an enhanced compressive strength of concrete. However, the time in obtaining the compressive strength is very important. While the lower activity of FA particles in the mix gives rise to retarded strength development of concrete at early ages, SF, in contrast, is a very reactive pozzolan with high pore filling ability thus resulted in accelerated strength development. The combined effect on the strength development may vary significantly at early ages. But, when concrete has been cured for longer time period, such as 56 days, the strength enhancement of concrete consisted of binary mixes due to the formation of additional CSH becomes more noticeable. When the concrete with a ternary mix of FA, SF and OPC is considered, its positive effect on the strength development remains. However, when the 28-day cube strength has been commonly used in various aspects, such as structural design, its use as an indicator for concrete durability requires more attention. When the strength development at 28 days is not yet complete, especially in the presence of FA, the 28-day strength apparently depends on the relative amount of FA and SF. It is suggested that the concrete strength at a longer time period, such as 56-day cube strength, is a better indicator of concrete durability. More research in this aspect is to be conducted.

5. Conclusions

A series of experimental tests on SCC mixes with various levels of OPC replacement by FA and SF have been carried out. Based on the test results, the following conclusions can be drawn:

1. Partial replacement of OPC by FA and SF in SCC reduces the surface water absorption and sorptivity.
2. When only fly ash is used to partially replace OPC, the reduction in sorptivity is noticeable when the amount of FA is greater than 20% replacement of OPC.
3. When both FA and SF are adopted in SCC mixes, the reduction in water absorption is higher than using FA alone. This indicates that the effect of SF is much higher than that of FA.
4. Use of both FA and SF in SCC mixes give rise to enhanced 28-day cube strength of SCC.
5. There is no obvious correlation between sorptivity and 28-day cube strength. The behavior of surface water absorption of SCC and its compressive strength depends on the proportion of mineral admixtures and other environmental factors. Concrete strength at a longer time period may serve as a better indicator of concrete durability.

When the optimized mix design of SCC is normally based on its fresh and hardened properties, the durability of SCC should be duly considered. Otherwise, use of SCC may lead to long-term maintenance needs.

Notation

i	cumulative amount of water absorbed per unit cross-sectional area of concrete (g/mm^2)
S	sorptivity coefficient (g/mm^2/min$^{1/2}$)
t	time measured in minutes (min)

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