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Shrinkage reduction of high strength fiber reinforced cementitious composites (HSFRCC) with various water-to-binder ratios

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ABSTRACT

In some applications of high strength fiber reinforced cementitious composites (HSFRCC), shrinkage is an important concern. From the literature, shrinkage can be reduced by the addition of shrinkage reducing admixture (SRA) or replacing Portland cement with sulfoaluminate cement (SAC). This investigation studies the effectiveness of SAC and SRA in reducing the shrinkage of HSFRCC. HSFRCC of water-to-binder ratios 0.19, 0.3 and 0.4 when Portland cement is employed, as well as 0.21, 0.3 and 0.4 with SAC, are tested under both sealed condition (to study autogeneous shrinkage) and drying condition. According to the test results, SAC is more effective in reducing shrinkage of HSFRCC with higher water-to-binder ratio whereas SRA is more effective for HSFRCC with lower water-to-binder ratio. Combined use of SAC and SRA can lead to very significant shrinkage reduction.

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1. Introduction

With the use of low water-binder ratio, incorporation of silica fume to improve packing between cement particles, and the addition of superplasticizers to facilitate flow, high strength cementitious materials with low porosity and discontinuous capillary pore structure can be made. Since high strength is accompanied by increased brittleness, micro-steel fiber is often added to produce high strength fiber reinforced cementitious composites (HSFRCC) for practical applications. In addition to high strength (compressive strength > 150 MPa and direct tensile strength of 8–10 MPa), HSFRCC possesses high toughness and a certain degree of strain hardening under tensile loading [1–4]. HSFRCC has been employed to produce thin and lightweight pre-cast elements that are assembled on the building site. Examples include components for footbridges, balconies, staircases and offshore structures [5–7]. The use of such components facilitates the construction process and is particularly beneficial when the structure is subjected to the severe environment.

Recently, HSFRCC has been employed for the joining of pre-cast components made with normal concrete. Conventionally, a relatively wide joint with transverse reinforcements has to be cast on site to ensure that loading is properly transferred between the pre-cast members on the two sides. Taking advantage of the excellent bond capacity between high-yield steel bar and HSFRCC, a much shorter joint can be made [5,8]. In addition, no transverse reinforcements need to be incorporated. Farhat et al. [9] has also demonstrated the application of HSFRCC to the retrofitting of concrete beams. In their work, HSFRCC strips are pre-fabricated and then bonded to concrete members with epoxy. Significant strengthening can be achieved. While this approach is suitable for relatively short members, it may not be convenient for large members, where either a very long plate have to be pre-fabricated and handled, or individual shorter plates have to be joined in a special way to ensure proper load transmission between the plate. Under such a situation, a better alternative is to apply a layer of HSFRCC directly on the surface of the concrete member, provided it has been roughened to provide sufficient interfacial bond.

In each of the above applications, shrinkage of the HSFRCC can be a concern. For the joining of pre-cast components, high shrinkage will result in residual tension that may lead to the formation of a crack at the HSFRCC/concrete interface, especially if the member itself is under high bending moment. In the repair application, high shrinkage can lead to significant stress concentrations at the free ends of the HSFRCC layer, causing peeling to occur. Also, in HSFRCC, the binder content is usually higher than that of normal concrete. Due to the reduction of aggregate/binder ratio, the skeleton support to resist shrinkage is also reduced. With low water-to-binder ratio and addition of silica fume forming to form a dense microstructure, the internal relative humidity (RH) drops rapidly during

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the hydration process, leading to higher autogenous shrinkage as a consequence of self-desiccation. To broaden the application of HSFRCC, shrinkage reduction is an important issue to be addressed.

Shrinkage reducing admixture (SRA) is able to reduce both drying shrinkage [10] and autogenous shrinkage [10,11] by lowering the surface tension of water in capillary pores. For drying shrinkage, capillary stress is a dominating mechanism when relatively humidity is within 45–90%. When pore water evaporates from the capillary pores, tension is transferred to the walls of pores causing drying shrinkage. Autogenous shrinkage occurs when self-desiccation leads to the emptying of pores inside the bulk cementitious material. The menisci present at the interfaces between water-filled and empty pores develop stresses within the liquid phase to induce shrinkage. As shrinkage reducing admixture can reduce the surface tension of water inside pores, both drying shrinkage and autogenous shrinkage can be reduced. Rongbing and Jian [10] showed the increased rate of free drying shrinkage reduction using higher content of SRA in concrete specimen. According to Bentz et al. [11], the addition of shrinkage reducing admixture leads to internal relatively humidity (RH) reduction in cement pastes and mortar with water-to-cement ratio of 0.3 under sealed condition.

Calcium sulfoaluminate cement (SAC) is a kind of high early strength cement containing belite (C_2S) and tetracalcium trialuminate sulfate ($C_4A_3\acute{S}$) as the main constituents, but no tricalcium aluminate (C_3A). $C_4A_3\acute{S}$ is mainly responsible for the early strength development by the rapid formation of ettringite. A significant fraction of the sulfoaluminate phase is consumed within a few hours of hydration and about 60–70% is consumed within the first 24 h [12]. SAC may or may not undergo expansion depending on the time and way of ettringite formation in the course of hydration. Specifically, when the ettringite is formed after the development of a rigid skeletal structure, expansion will occur to compensate for shrinkage. Zhang et al. [13] showed that the replacement of Portland cement by SAC would significantly reduce the drying shrinkage of fiber cementitious composites made with 1.7% of PVA fibers and high binder content. However, to the authors' knowledge, the shrinkage behavior of HSFRCC made with SAC is yet to be studied.

In this investigation, the use of SRA and SAC to reduce shrinkage in high strength fiber reinforced cementitious composites (HSFRCC) is investigated. In all samples, 2% of steel microfibers are added. To understand the shrinkage behavior of HSFRCC with various water-to-binder (w/b) ratios, specimens with w/b ratios 0.19, 0.3 and 0.4 were prepared. For specimens using SAC instead of PC, those with w/b ratios 0.21, 0.3 and 0.4 were prepared as the w/b ratio of 0.19 was found to be too low for proper flow. As will be shown later, the strength of Portland cement HSFRCC with w/b = 0.19 and SAC-HSFRCC with w/b = 0.21 are similar. According to Loukili et al. [14], the shrinkage of HSFRCC (with 6% of fiber) is just about 15% lower than that without fiber. In other words, fiber incorporation does reduce shrinkage but not to a large extent. The conclusions drawn from this study regarding the effect of SAC and SRA on shrinkage behavior should therefore also applied to HSFRCC of similar matrix composition but different fiber content (including the case without fibers).

In the following, the experimental program for measuring autogenous shrinkage as well as shrinkage under drying of HSFRCC is described. The effectiveness of using SAC and SRA in reducing the shrinkage of HSFRCC with very low water/binder ratios (0.19 and 0.21) will be presented first, followed by results on HSFRCC with water/binder ratios of 0.3 and 0.4. For HSFRCC with low water/binder ratio, the measured shrinkage under drying condition also includes the contribution of self-dessication. Therefore, the term 'shrinkage under drying' is preferred over 'drying shrinkage' in this paper.

2. Experimental details

2.1. Material

Table 1 shows the mix compositions of HSFRCC studied in our work. Three water/binder ratios (0.19, 0.3 and 0.4) were considered. The binder was composed of Portland cement, fly ash and silica fume, which are common ingredients for high strength concrete [15]. As the spherical shape of fly ash facilitates particle flow, its use can reduce the required water content for a given consistency. In this study, 20% by mass of Portland cement was replaced by fly ash to reduce the water demand of the fresh concrete. Silica fume is a key ingredient in high strength concrete. According to Caliskan [16], presence of silica fume gives denser and less porous transition zones, resulting in higher compressive strength of the matrix. However, according to Yang and Zhang [17], the increase of silica fume content in the mix also leads to higher autogenous shrinkage due to low internal RH of the matrix. In this study, the weight fraction of silica fume was limited to 5% of the total solid weight. As high strength cementitious matrix is very brittle, fibers should be added to provide sufficient toughness to prevent material shattering at ultimate failure. In addition to compensating for the brittle failure of high strength cementitious matrix, the incorporation of micro-steel fiber can improve the tensile strength of the composites. Wille et al. [18] showed the improvement on ultimate tensile strength (from 8 to 14 MPa) as well as the maximum post-cracking strain (from 0.17% to 0.24%) by increasing micro-steel fiber content from 1.5% to 2.5%. In this study, micro-steel fiber with diameter 0.16 mm and length 13 mm was used at volume fraction of 2%. As the presence of coarse aggregate could affect the distribution of steel fiber and reduce its bridging efficiency, only silica sand ($\leqslant$1.2 mm in size) is employed. Higher final shrinkage of HSFRCC can be caused by both high binder content and smaller maximum size of aggregate. There is hence a need to study methods to reduce shrinkage, such as the use of SAC or SRA. In all mixes, polycarboxylate superplasticizer (from BASF) is added to achieve self-compatibility of the mix.

Table 2 shows the mix compositions of SAC-HSFRCC in our study. As the water requirement for SAC to form paste was found to be higher than Portland cement, the lowest water/binder ratio for SAC-HSFRCC was taken to be 0.21 (rather than 0.19). In addition, specimens with water/binder ratio of 0.3 and 0.4 were also prepared. As SAC is a high early strength cement that can undergo initial setting within 30 min, retarder is required to make proper casting feasible. Boric acid was used in this study and the boric acid/cement ratio was 1% by weight.

Another way to reduce shrinkage is the addition of SRA. The SRA used in this research is Eclipse Floor from W.R. GRACE & Co.-Conn. The typical dosage of Eclipse Floor is in the range of 2.5–7.5 L/m^3, but doses as high as 12.5 L/m^3 can be used. In this investigation, specimens were made with SRA added to each of the mixes shown

Table 1
Mix proportions of PC-HSFRCC.

Cement (%)	Fly ash (%)	Silica fume (%)	Silica sand[a]			w/b	[b]SP/B (%)	Steel fiber (vol. fraction) (%)
			Type 1 (%)	Type 2 (%)	Type 3 (%)			
PC-HSFRCC-0.19								
45	11	5	6.3	14.1	18.6	0.19	0.84	2
PC-HSFRCC-0.3								
45	11	5	6.3	14.1	18.6	0.3	0.155	2
PC-HSFRCC-0.4								
45	11	5	6.3%	14.1	18.6	0.4	0.08	2

[a] Silica sand: Type 1: 300–1180 μm, Type 2: 150–600 μm, Type 3: 53–300 μm.
[b] BASF superplasticizer: (a) ACE80: 80%, (b) B211: 20%.

Table 2
Mix proportions of SAC-HSFRCC.

Sulfoaluminate cement (SAC) (%)	Fly ash (%)	Silica fume (%)	Silica sand[a]			w/b	[b]SP/B (%)	Steel fiber (%)	Boric acid/SAC (%)
			Type 1 (%)	Type 2 (%)	Type 3 (%)				
SAC-HSFRCC-0.21									
45	11	5	6.3	14.1	18.6	0.21	0.84	2	1
SAC-HSFRCC-0.3									
45	11	5	6.3	14.1	18.6	0.3	0.155	2	1
SAC-HSFRCC-0.4									
45	11	5	6.3	14.1	18.6	0.4	0.08	2	1

[a] Silica sand: Type 1: 300–1180 μm, Type 2: 150–600 μm, Type 3: 53–300 μm.
[b] BASF superplasticizer: (a) ACE80: 80%, (b) B211: 20%.

in Tables 1 and 2, with dosage fixed at 12.5 L/m^3. In total, with three water/binder ratios, two kinds of cement and presence/absence of SRA, twelve batches of specimens were prepared. The various kinds of specimens are summarized in Table 3.

2.2. Mixing procedure

All the binder and silica sand were first mixed for 1–2 min. If SAC was used, retarder (boric acid) was added before mixing. Superplasticizer was mixed to the water and added to the dry mixture for another 8 min to form self compacting mortar. Fibers were then added when mixing was continued for another 3–4 min.

2.3. Specimen preparation and test method

In this study, the shrinkage under drying and autogenous shrinkage of HSFRCCs were both measured. Under sealed condition with uniform temperature distribution during hydration, the autogenous deformation in the cross section of specimens is constant. However, for drying shrinkage, it is easier for free water near the specimen surface to evaporate and this induces moisture gradients in the cross section. The measured drying shrinkage then becomes dependent of the specimen size. In the case of high strength concrete, the dense microstructure makes it difficult for free water inside specimen to transport to the specimen surface. When large specimens are tested, the measured shrinkage under drying could be similar to the autogenous shrinkage as drying only occurs in a thin surface layer and its effect on overall shrinkage is small. To highlight the difference between the two kinds of shrinkage, specimens with 25 mm (width) × 25 mm (height) × 285 mm (length) were used in this experiment. Following ASTM C157, the shrinkage deformation was measured along the line joining the center of all cross sections. To facilitate the measurement, steel studs with a round tip were fixed at the two opposite ends of the specimen.

Table 3
HSFRCC specimens.

Batch	Material	Shrinkage reducing admixture (SRA)	Water/binder ratio
Batch 1	PC	No	0.19
Batch 2	PC–SRA	Yes	
Batch 3	SAC	No	0.21
Batch 4	SAC–SRA	Yes	
Batch 5	PC-0.3	No	0.3
Batch 6	PC–SRA-0.3	Yes	
Batch 7	SAC-0.3	No	
Batch 8	SAC–SRA-0.3	Yes	
Batch 9	PC-0.4	No	0.4
Batch 10	PC–SRA-0.4	Yes	
Batch 11	SAC-0.4	No	
Batch 12	SAC–SRA-0.4	Yes	

Six specimens were prepared for each batch (three for shrinkage measurement under drying and three for autogenous shrinkage measurement). As chemical shrinkage starts together with the cement hydration process, shrinkage takes place before hardening of the specimens. However, when the specimen is still in plastic state, the developed shrinkage does not induce stress and cracking. In other words, while the shrinkage during plastic state may be of scientific interest, it does not have significant influence on the structure behavior. For engineering applications, it may be more reasonable to measure the shrinkage after hardening of the specimen. In this study, a number of cubes were cast together with each batch of shrinkage specimens and cured under the same condition. The cubes were tested in compression at different times within the first 12 h. Once the cube strength reached 3–5 MPa, the concrete was considered as hardened. In our tests, HSFRCC specimens of very low water/binder ratios (0.19 and 0.21) reached 3–5 MPa at about 6–10 h after casting depending on the cement type and presence/absence of SRA. With water/binder ratios of 0.3 and 0.4, hardening was reached after 18 h.

Once the concrete reached the hardened state, the shrinkage specimens were demoulded and its length was measured immediately to give the initial reading. Out of the six specimens, three were sealed by several layers of low density polyethylene (LDPE) and a layer of polypropylene. These specimens are kept at constant temperature of 25 °C and autogenous shrinkage was measured at various times (note: wrapped specimens with the same composition placed in wet and dry conditions gave similar autogenous shrinkage values. The effectiveness of the wrapping method is thus verified). The other three specimens were employed for the measurement of shrinkage under drying. Following ASTM 596, these specimens were water cured for 3 days at 25 °C after hardened state. They are then placed under drying condition with controlled humidity of 50 ± 5%.

For both autogenous shrinkage and shrinkage under drying, length measurement is carried out daily in the first few weeks. With reduced shrinkage rate over time, the time between subsequent readings increased to several days. The final reading was taken either when the shrinkage value did not change anymore, or when the measurement time exceeded 3 months.

3. Results and discussion

In this section, results on HSFRCC's with low water/binder ratio (0.19 for PC and 0.21 for SAC) and higher water/binder ratios (0.3 and 0.4 for both kinds of cement) will be discussed separately due to two reasons. First, the shrinkage mechanisms are different, with autogenous shrinkage being the major mechanism at low water/binder ratio while drying shrinkage dominant at higher water/binder ratios. Second, the effects of SAC and SRA on shrinkage are found to be very different at lower and higher water/binder ratios. It is therefore better to discuss the results separately.

3.1. Shrinkage of HSFRCC of low water/binder ratios (0.19 for PC, 0.21 for SAC)

Before discussing the shrinkage behavior, it is of interest to look at the strength of HSFRCC's containing SRA. According to Folliard and Berke [19], 6–8% reduction in 28-day compressive strength were recorded for specimens of water/binder ratio 0.35 containing 1.5% addition of SRA in weight fraction of binder, cured at 20 °C and 100% RH. On the other hand, Bentz et al. [11] showed no significant reduction of 28-day compressive strength for water-to-binder ratio 0.35 (8% silica fume) mortar cylinders cured under sealed conditions at 30 °C. The effect of SRA on concrete strength is hence inconclusive. Table 4 gives the average 28-day cube compressive strengths of PC-HSFRCCs and SAC-HSFRCCs specimens of water/binder ratios 0.19 and 0.21. As shown in the table, the measured values of HSFRCCs (for both PC and SAC) with and without SRA are all similar and between 136.5 and 138 MPa. In our case, the addition of SRA has not caused reduction of compressive strength.

Figs. 1 and 2 show the shrinkage under drying and autogenous shrinkage of the PC-HSFRCCs and the SAC-HSFRCCs. For each composition, a typical curve is shown. However, it should be pointed out that the shrinkage vs time curves for specimens of the same composition are very close to one another. The average final shrinkage measurements from three specimens are summarized in Table 5. The autogenous shrinkage of PC-HSFRCC of water-to-binder ratio 0.19 is 548×10^{-6}. According to Loukili et al. [14], the autogenous shrinkage of HSFRCC with 6% micro-steel fiber and without fiber (water/binder ratio 0.16) is about 500×10^{-6} and 580×10^{-6}. Yang et al. [20] reported the autogenous shrinkage of high strength concrete (water/binder ratio 0.25) is about 300×10^{-6}. The autogenous shrinkage of the PC-HSFRCC in this study is therefore very similar to that of the HSFRCCs investigated in Loukili's study. Compared to Yang's result, the autogenous shrinkage is relatively higher. According to Jensen and Hansen [21], in high strength concrete, the low water/binder ratio and the addition of silica fume cause a significant drop in the internal relative humidity (RH) in the cement paste during sealed hydration. Closely related to this autogenous RH-change, the cement paste undergoes autogenous shrinkage. Jensen and Hansen [22] summarized studies on autogenous deformation and RH-change

Table 4
The 28-day cube compressive strengths of HSFRCC specimens.

Batch	Material	Average 28-day cube compressive strength (MPa)
Batch 1	PC	138
Batch 2	PC–SRA	137
Batch 3	SAC	137.3
Batch 4	SAC–SRA	136.5

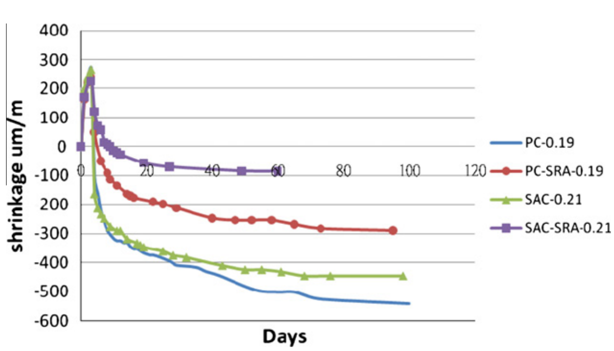

Fig. 1. Shrinkage of HSFRCCs under drying conditions.

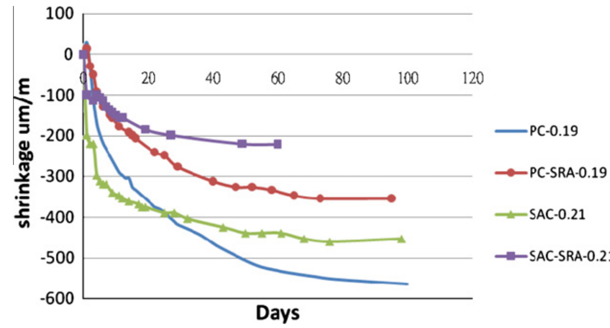

Fig. 2. Shrinkage of HSFRCCs under sealed conditions.

Table 5
Final shrinkage value of HSFRCC specimens.

Batch	Material	Average value under drying conditions ($\times 10^{-6}$)	Average autogenous shrinkage under sealed conditions ($\times 10^{-6}$)
Batch 1	PC-0.19	533	548
Batch 2	PC–SRA-0.19	297	363
Batch 3	SAC-0.21	445	452
Batch 4	SAC–SRA-0.21	87	210
Batch 5	PC-0.3	961	310
Batch 6	PC–SRA-0.3	742	296
Batch 7	SAC-0.3	436	202
Batch 8	SAC–SRA-0.3	268	90
Batch 9	PC-0.4	1177	213
Batch 10	PC–SRA-0.4	1023	187
Batch 11	SAC-0.4	461	85
Batch 12	SAC–SRA-0.4	339	71

and stated that both autogenous deformation and RH-change are influenced by many factors (for example w/c ratio, cement composition, silica fume content, fineness of cement and silica fume, volume of aggregate and exposure temperature). However, there is a remarkable lack of agreement on the extent of influence of the different factors. One of the general characteristics is a lowering of the w/c ratio which promotes autogenous shrinkage and RH-change. Owing to the similarity of silica fume/binder ratio in Yang's study and this study, the lower water/binder ratio can explain the higher autogenous shrinkage.

According to the test results in Table 5, the shrinkage under drying for PC-HSFRCC (water/binder = 0.19) and SAC-HSFRCC (water/binder = 0.21) are even smaller than the corresponding autogenous shrinkage. A major reason is the swelling due to water absorption during the first three days of curing (with the specimens immersed inside water after demolding). If one considers the total shrinkage measured after the initial swelling (which is given in Table 6), the average ultimate values are 812×10^{-6} for PC-HSFRCC and 711×10^{-6} for SAC-HSFRCC respectively. Subtracting the corresponding values for autogeneous shrinkage in Table 5, the drying components of shrinkage are 264×10^{-6} and 259×10^{-6}. For both compositions with low water/binder ratios, the autogenous shrinkage, which is about twice the drying component of shrinkage, is the dominating mechanism.

3.1.1. Effect of replacing PC by SAC

From Table 5 (batch 1 and 3), when PC is replaced by SAC in the mix, the autogenous shrinkage reduces by 18% while the shrinkage under drying reduces by 16.5%. The mechanism of shrinkage reduction by SAC is the fast formation of ettringite by hydration of $C_4A_3\acute{S}$. For HSFRCC, the water-to-binder ratio is as low as 0.19–0.21, so a significant portion (could be about 50%) of cement may stay unreacted, and hence does not contribute to the shrinkage

Table 6
Shrinkage under drying for various HSFRCC specimens with initial zero reading taken after 3 days of curing.

Batch	Material	Average shrinkage under drying conditions ($\times 10^{-6}$)
Batch 1	PC-0.19	812
Batch 2	PC–SRA-0.19	530
Batch 3	SAC-0.21	711
Batch 4	SAC–SRA-0.21	312
Batch 5	PC-0.3	1145
Batch 6	PC–SRA-0.3	827
Batch 7	SAC-0.3	608
Batch 8	SAC–SRA-0.3	389
Batch 9	PC-0.4	1385
Batch 10	PC–SRA-0.4	1115
Batch 11	SAC-0.4	650
Batch 12	SAC–SRA-0.4	431

reduction. This explains the modest reduction in shrinkage when PC is replaced by SAC.

In Fig. 2, the development rate of autogenous shrinkage for SAC-HSFRCC specimens in the first few days is higher than that of PC-HSFRCC specimens. As rate of hydration of SAC at early age is higher than PC, the development of self-desiccation causing autogenous shrinkage is also faster. This explains the higher shrinkage rate during the first few days.

3.1.2. Effect of SRA

From the results in Table 5 (batch 1–4), when SRA is added to mixes, the autogenous shrinkage of PC-HSFRCC and SAC-HSFRCC reduces by about 34% and 54% respectively. The corresponding reduction in shrinkage under drying condition is 44% and 80%. These results indicate the high effectiveness of SRA in reducing shrinkage of HSFRCC with low water/binder ratios. SRA reduces shrinkage by reducing the surface tension of water in capillary pores. In our experiment, the maximum SRA dosage recommended by the supplier was employed. In mixes with low water/binder ratio, the water content is also low, and the high dosage of SRA is shown to be very effective in reducing the autogenous shrinkage.

When both SRA and SAC are employed, the reduction in autogenous and shrinkage under drying are 62% and 84% respectively. This result is of great practical interest. From the scientific point of view, the use of both SRA and SAC seems to create a synergism. For example, when SAC is used instead of PC, the addition of SRA reduces shrinkage by a higher amount. The exact reason of this is unknown and should be addressed in future investigations.

3.1.3. Shrinkage measurement under drying of HSFRCC (initial measurement taken after water curing)

As mentioned before, swelling of the sample during initial curing can reduce the final total shrinkage under drying condition because the shrinkage that has been compensated by swelling has been 'subtracted' in the final reading. Under practical curing conditions, it may not be possible for a concrete member to swell to the extent of the laboratory specimen. According to ASTM and British Standards, concrete shrinkage is measured only after drying starts. In other words, the initial reading is taken right after water curing is stopped and the specimens transferred to the drying environment (which is 3 days in our case). To provide additional information, we have re-plotted our shrinkage data in Fig. 3 with initial reading (zero shrinkage) taken after 3 days so the initial swelling is neglected. The average ultimate drying shrinkage values are summarized in Table 6. The ultimate shrinkage of PC-HSFRCC, PC-HSFRCC–SRA, SAC-HSFRCC as well as SAC-HSFRCC–SRA (batch 1–4) is 812×10^{-6}, 530×10^{-6}, 711×10^{-6} and 312×10^{-6} respectively. Again, the use of SRA is found to be more effective than SAC

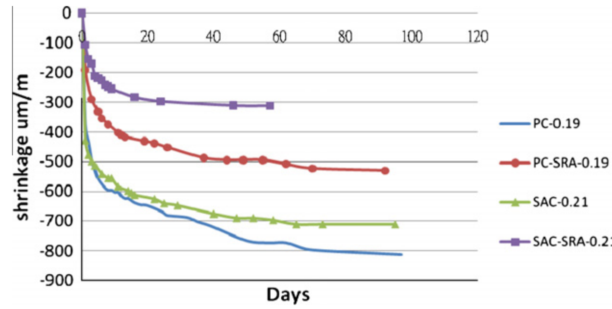

Fig. 3. Shrinkage of HSFRCCs under drying conditions (initial zero reading taken after 3 days of water curing).

in reducing shrinkage and the combined use of SRA and SAC can reduce the drying shrinkage by over 60%.

3.2. Shrinkage of HSFRCC of water/binder ratios 0.3 and 0.4

For specimens with higher water/binder ratios (0.3 and 0.4), the corresponding compressive strengths are about 100 MPa and 70 MPa. The average ultimate values of autogenous shrinkage and shrinkage under drying are summarized in Table 5 (batch 5–12). As expected, the autogenous shrinkage is much smaller than that under drying condition. This is because the higher water/binder ratio mixes contain more free water so the self-dessication effect is less significant. Therefore, only results on shrinkage under drying are plotted, and discussions of the effect of SRA and SAC will focus on this situation alone. Figs. 4 and 5 show the shrinkage behavior for PC-HSFRCC as well as SAC-HSFRCC specimens with and without SRA, for water/binder ratios of 0.3 and 0.4, respectively. In comparison to the low water/binder ratio mixes, the shrinkage under drying conditions has increased . This is due to the higher water content inside the specimens as well as its higher permeability.

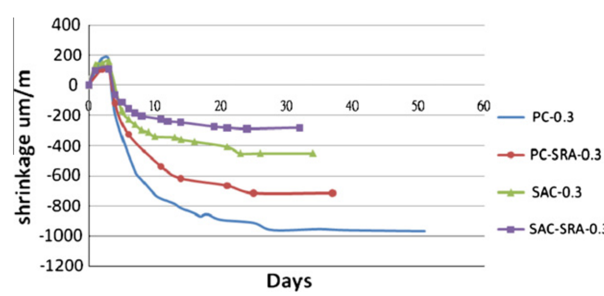

Fig. 4. Drying shrinkage of PC-HSFRCC and SAC-HSFRCC of w/b 0.3.

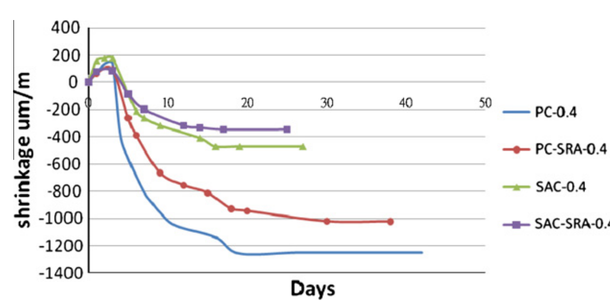

Fig. 5. Drying shrinkage of PC-HSFRCC and SAC-HSFRCC of w/b 0.4.

3.2.1. Effect of replacing PC by SAC

From the results in Table 5 (batch 5 and 6), for HSFRCC with water/binder ratio of 0.3, replacing PC with SAC can reduce the shrinkage by 55%. When the water/binder ratio is 0.4, the corresponding shrinkage reduction is 61%. Unlike the case with low water/binder ratio, the use of SAC can reduce the shrinkage of higher water/binder HSFRCC by more than one-half. This could be explained by the formation of more ettringites in mixes with more water, and the resulting expansion compensates part of the drying shrinkage.

3.2.2. Effect of SRA

Adding SRA can also reduce the shrinkage development under drying of both PC-HSFRCC and SAC-HSFRCC specimens. The shrinkage reduction for PC-HSFRCC-0.3 and SAC-HSFRCC-0.3 is 22% and 39%. For PC-HSFRCC-0.4 and SAC-HSFRCC-0.4, the reduction is 13% and 26%. Comparing with the use of SAC, adding SRA to higher water/binder HSFRCC is less effective in reducing the shrinkage under drying conditions. It should be mentioned that the maximum recommended dosage of SRA has been added to all of our mixes (with lower or higher water/binder ratio). With the same dosage of SRA, the reduction in surface tension for mixes with higher water/binder ratios is less than that in those with low water/binder ratios.

The above comparison also indicates that the addition of SRA (at the same dosage) reduces shrinkage more effectively when SAC is used instead of PC in the mix. This is also observed for HSFRCC of low water/binder ratio.

3.2.3. Shrinkage measurement under drying of HSFRCC of water-to-binder ratios 0.3 and 0.4 (initial measurement taken after water curing)

Figs. 6 and 7 show the drying shrinkage result of HSFRCC with water/binder ratios 0.3 and 0.4, taking after the initial water curing period (i.e., initial zero reading taken at 3 days). The ultimate drying shrinkage values are also summarized in Table 6. From the table, the ultimate shrinkage values for PC-HSFRCC, PC-HSFRCC–SRA, SAC-HSFRCC as well as SAC-HSFRCC–SRA of water/binder ratio 0.3 (batch 5–8) are 1145×10^{-6}, 827×10^{-6}, 608×10^{-6} and 389×10^{-6} respectively. For water/binder ratio of 0.4 (batch 9–12), the ultimate shrinkage values of PC-HSFRCC, PC-HSFRCC–SRA, SAC-HSFRCC as well as SAC-HSFRCC–SRA are 1385×10^{-6}, 1115×10^{-6}, 650×10^{-6} and 431×10^{-6} respectively. Two conclusions can again be drawn. For mixes with higher water/binder ratios, SAC is more effective than SRA in reducing shrinkage. Combined use of SRA and SAC is very effective, resulting in shrinkage reduction of 64% and 69% for mixes with 0.3 and 0.4 water/binder ratios, respectively.

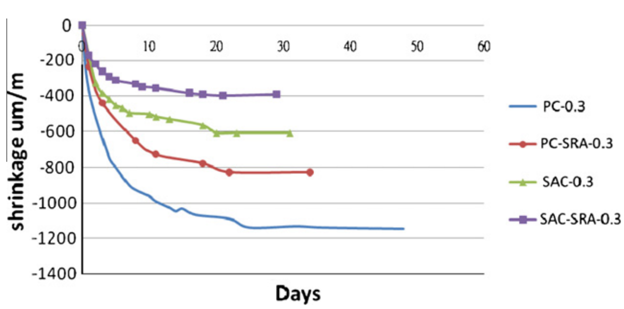

Fig. 6. Drying shrinkage of PC-HSFRCC and SAC-HSFRCC of w/b 0.3 (initial zero reading taken after 3 days of water curing).

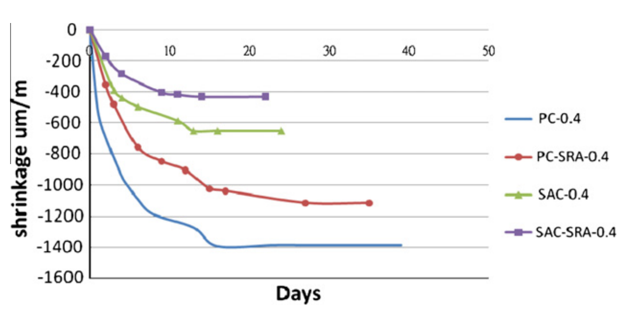

Fig. 7. Drying shrinkage of PC-HSFRCC and SAC-HSFRCC of w/b 0.4 (initial zero reading taken after 3 days of water curing).

3.3. Shrinkage under drying of HSFRCCs with different water/binder ratios

Before ending, it is informative to look at the trend of shrinkage with water/binder ratio. Here, shrinkage under drying condition (measured from initial hardening) is considered. From the results in Table 5, the ultimate shrinkage values of PC-HSFRCC with w/b ratio 0.19 (batch 1), PC-HSFRCC-0.3 (batch 5) and PC-HSFRCC-0.4 (batch 9) are 533×10^{-6}, 961×10^{-6} and 1177×10^{-6}. The shrinkage of those specimens with SRA (batch 2, 6 and 10) are 297×10^{-6}, 742×10^{-6} and 1023×10^{-6}. The trend is reasonable as the shrinkage under drying should increase with water/binder ratios regardless of the presence of SRA.

The ultimate shrinkage under drying of SAC-HSFRCC with water-to-binder ratio 0.21 (batch 3), SAC-HSFRCC-0.3 (batch 7) and SAC-HSFRCC-0.4 (batch 11) are 445×10^{-6}, 436×10^{-6} and 461×10^{-6}. The drying shrinkage of HSFRCC with higher water/binder ratio should be higher as there is more evaporable water as well as a higher paste/sand ratio. However, as discussed in previous sections, SAC is more effective in reducing shrinkage for HSFRCC with higher water/binder ratio due to higher degree of hydration of SAC. Due to the compensating effect of the two mechanisms, the shrinkage of SAC-HSFRCC with different water/binder ratios under drying condition is found to be similar.

When SRA is added to HSFRCC made with SAC (batch 4, 8 and 12), the ultimate shrinkage values are 87×10^{-6}, 268×10^{-6} and 339×10^{-6}. The increase of shrinkage can be explained by the reduced effectiveness of SRA with increased water/binder ratio when the same dosage is added to all mixes.

4. Conclusions

This study focuses on the shrinkage reduction of high strength fiber reinforced cementitious composites (HSFRCC) with various water/binder ratios from 0.19 to 0.4. Two approaches for reducing shrinkage, namely, the replacement of Portland cement (PC) with sulfoaluminate cement (SAC) and the addition of shrinkage reducing admixture (SRA), are investigated. Testing is performed under drying condition as well as sealed condition. Based on the experimental results, the following conclusions can be made:

(1) The replacement of PC by SAC and the addition of SRA are both feasible methods to reduce the shrinkage of HSFRCC under drying or sealed conditions.
(2) The use of SRA does not affect the 28-day compressive strength of HSFRCCs.
(3) For HSFRCC with low water/binder ratio (0.19 for PC, 0.21 for SAC), the addition of SRA is more effective in reducing shrinkage than replacing PC with SAC.
(4) For HSFRCC with higher water/binder ratios (0.3 and 0.4), replacing PC with SAC is more effective in reducing shrinkage than the use of SRA.

(5) The combined use of SAC and SRA is very effective in reducing the shrinkage of HSFRCC. For the compositions tested in this study, shrinkage under drying condition decreases by over 80% when the water/binder ratio is around 0.2, while the reduction is over 70% for mixes with water/binder ratios of 0.3 and 0.4.

Although the investigation is on HSFRCC, we believe the same conclusions apply to high strength cementitious composites without fibers, because both SAC and SRA affects the shrinkage performance of the matrix but have no effect on the fibers.

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