Available online at www.sciencedirect.com
ScienceDirect
Cement & Concrete Composites 29 (2007) 690–699
Cement & Concrete Composites
www.elsevier.com/locate/cemconcomp

Shrinkage of plain and silica fume cement concrete under hot weather

O.S.B. Al-Amoudi, M. Maslehuddin *, M. Shameem, M. Ibrahim

King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

Received 8 October 2006; received in revised form 2 May 2007; accepted 4 May 2007
Available online 23 May 2007

Abstract

Supplementary cementing materials (SCMs) are widely used these days to improve the durability of concrete. Silica fume has gained world wide acceptance due to its high pozzolanic reactivity compared to other SCMs. While silica fume cement concrete has several advantages over other blended cement concretes its main draw back is increased plastic and drying shrinkage, particularly under hot weather conditions. This paper reports results of a study conducted to assess these properties of plain and silica fume cement concrete specimens cast and cured in the field under hot weather conditions. The effect of specimen size and method of curing on plastic and drying shrinkage and some of the mechanical properties of silica fume and plain cement concrete specimens were evaluated. Results indicated that the type of cement significantly affected both the plastic and drying shrinkage of concrete in that these values in the silica fume cement concrete specimens were more than those in the plain cement concrete specimens. As expected, the shrinkage strains in both the plain and silica fume cement concrete specimens cured by continuous water-ponding were less than that in similar concrete specimens cured by covering them with wet burlap. The results point to the importance of selecting a good quality silica fume and good curing for avoiding cracking of concrete due to plastic and drying shrinkage, particularly under hot weather conditions.

Keywords: Plain and silica fume cement concretes; Plastic and drying shrinkage; Curing; Hot weather; Field exposure; Mechanical properties

1. Introduction

The climatic conditions in the hot and arid areas of the world are considered to be very aggressive for concrete. The climatic factors in these regions are typically manifested by large fluctuations in the daily and seasonal temperature and humidity. The temperature can vary by as much as 30 °C during a typical summer day, and the relative humidity ranges between 40 and 100% over a period of 24 h. These sudden and continuous variations in temperature and humidity accelerate the cracking of concrete due to expansion/contraction.

The low durability of concrete in the hot and humid areas of the world has directed the attention of concrete technologists to search for concrete admixtures to improve the quality of concrete to cope with the aggressive exposure conditions. Research conducted earlier indicated the great potential of SCMs in enhancing concrete durability. Among the SCMs researched, silica fume has displayed distinctly superior performance [1,2]. The important characteristics that make silica fume suitable in improving the properties of concrete are [3]:

(i) It is a very fine powder with an average particle diameter 100 times finer than that of ordinary Portland cement,
(ii) its spherical shaped particles increase the lubrication effect in the cement,
(iii) its glassy particles enhance its reactivity with cement, and
(vi) its high amorphous silica content makes it a super-pozzolanic material.

Silica fume is a by-product of the manufacture of silicon and ferrosilicon alloys. Its use is expected to produce dense and impermeable concrete. Its increasing usage has been

* Corresponding author. Tel.: +966 3 860 2853; fax: +966 3 860 3996.
E-mail address: muddin@kfupm.edu.sa (M. Maslehuddin).

0958-9465/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2007.05.006

promoted due to economic, technical and environmental considerations. However, in some parts of the world, it is used due to the technical necessity rather than the economic benefit. One of the major drawbacks of silica fume cement concrete, particularly under the hot weather conditions is the development of plastic and drying shrinkage cracks, particularly if the concrete is not inadequately cured.

Plastic shrinkage cracks often appear within the first three to 36 h after casting of large surface area concrete members [3]. Stringent and extended duration of curing is often recommended to avoid plastic shrinkage cracking of silica fume cement concrete. Even with proper and early curing, field observations indicate that cracking may sometimes develop in thin and large surface area to depth ratio structural concrete members. Drying shrinkage cracks may also be noted in the silica fume cement concrete due to the accelerated pozzolanic reaction that consumes the mixing water very rapidly.

In spite of the known advantages of silica fume, the development of plastic and drying shrinkage cracks is of principal concern to the users of this type of concrete in hot and arid regions, particularly in the structural members of large surface area to depth ratio. The limited number of papers generally indicate that if conditions are favorable for plastic shrinkage to occur, then silica fume cement concrete would be more prone to such shrinkage and cracking than ordinary Portland-cement concrete [4]. This is attributed to the fact that silica fume cement concrete exhibits little or no bleeding thus allowing very little water to rise to the surface; hence, the risk of cracking is higher in fresh silica fume cement concretes. Also, the consumption of mix water due to the accelerated pozzolanic reaction of silica fume leads to accelerated shrinkage of concrete.

This field study was conducted to evaluate plastic and drying shrinkage characteristics of silica fume cement concrete exposed to hot weather conditions. The effect of curing methods and the specimen size on the aforesaid parameters was also evaluated. Plastic and drying shrinkage of plain cement concrete were also evaluated for comparison purposes.

2. Methodology of research

2.1. Preparation and curing of concrete specimens

Slab specimens, two each measuring 300 × 300 × 30 cm, and 500 × 500 × 30 cm, were prepared. One half of the slab specimens were prepared with plain cement concrete while the other half were prepared with the silica fume cement concrete.

Plain and silica fume cement concrete specimens were prepared with a cementitious materials content of 350 kg/m^3 and water to cementitious materials ratio of 0.45. In the silica fume cement concrete, silica fume constituted 8% of the total quantity of the cementitious material.

After casting and finishing, the concrete specimens were covered with plastic sheets for 24 h. During this time, plastic shrinkage measurements were conducted on the slab specimens. After 24 h, half of the concrete slab specimens were cured by covering them with wet burlap while the other half was cured by water-ponding. The plain cement concrete specimens were cured for seven days while the silica fume cement concrete slab specimens were cured for 21 days.

2.2. Monitoring of concrete specimens

The concrete specimens were visually inspected to monitor and map cracks, if any. Plastic shrinkage measurements were conducted for 24 h after casting while drying shrinkage measurements were conducted after the completion of the curing period.

2.2.1. Measurement of plastic shrinkage strain

Plastic shrinkage strain was measured by embedding aluminum strips (measuring 25 × 150 × 6 mm) to a depth of 100 mm in the slab concrete specimens. The strips were placed at the mid-section of each of the four sides of the specimen. The movement of the strips was monitored using linear variable differential transducers (LVDTs) that were connected to a data acquisition system for a period of 24 h. Shrinkage readings were recorded every 10 min during the first 400 min and every 30 min thereafter.

Figs. 1 and 2 show the placement of the LVDTs and the arrangement for measuring the plastic shrinkage strain.

2.2.2. Measurement of drying shrinkage strain

The drying shrinkage strain was measured after the completion of the curing. This was done by embedding demec gauges on the surface of the concrete specimens. Five pairs of demec gauges were fixed on each specimen. Drying shrinkage was measured every two weeks by

Fig. 1. Concrete specimen with LVDTs for measuring the plastic shrinkage strain.

Fig. 2. Close up view of the LVDT used for plastic shrinkage strain measurements.

measuring the length between the demec gauges with the help of an extensometer. Fig. 3 shows the process of measuring the drying shrinkage.

2.3. Evaluation of concrete properties

Sufficient cylindrical concrete specimens 75 mm in diameter and 150 mm high were cast from each concrete mixture. These cylinders were cast in the field along with the slab specimens and thereafter cured under both field and laboratory conditions and tested to determine the compressive strength, split tensile strength, and pulse velocity according to ASTM C 39, ASTM C 496 and ASTM C 597, respectively.

The aforesaid tests were conducted after three, seven, 14, 28, 90 and 180 days of water curing under laboratory conditions and under wet burlap in the field.

Fig. 3. Measurement of drying shrinkage strain using an extensometer.

3. Results

3.1. Plastic shrinkage strain

Fig. 4 is a typical presentation of the plastic shrinkage strain in the large (5×5 m) plain cement concrete specimen. The average plastic shrinkage strain is also included in this figure. The data in Fig. 4 indicate that the plastic shrinkage increased with the period of exposure to the ambient conditions. The increase in plastic shrinkage strain continued up to about 1000 min reaching an average maximum value of about 460 μm.

Fig. 5 depicts the average plastic shrinkage strain in the small (3×3 m) plain and silica fume cement concrete specimens. The data therein display a trend similar to that noted in Fig. 4, whereby the plastic shrinkage strain increased with time. Further, the plastic shrinkage strain in the silica fume cement concrete specimen was more than that in the plain cement concrete specimen. After about 1000 min of casting, the plastic shrinkage strain in the plain and silica fume cement concrete specimens was 440 and 756 μm, respectively.

Fig. 6 depicts the average plastic shrinkage strain in the 5×5 m plain and silica fume cement concrete specimens. The data therein indicate a trend similar to that noted in Fig. 5, whereby the plastic shrinkage strain increased with time of casting and that the plastic shrinkage strain in the silica fume cement concrete specimen was more than that in the plain cement concrete specimen. After about 1000 min of casting, the plastic shrinkage strain in the plain and silica fume cement concrete specimens was 457 and 785 μm, respectively.

A comparison of data in Figs. 5 and 6 indicates that the shrinkage of 5×5 m concrete specimens was more than that of 3×3 m concrete specimens. However, the difference between the two sets of data was very small. The maximum plastic shrinkage strain in the 5×5 m concrete plain cement concrete specimen was 457 μm while it was 440 μm in the 3×3 m concrete specimen. These values in the silica fume cement concrete specimen were 785 and 756 μm, respectively.

3.2. Drying shrinkage strain

The drying shrinkage measurements were taken after the completion of curing, which was 7 days for plain cement concrete and 21 days for silica fume cement concrete.

The drying shrinkage strain in the big (5×5 m) plain and silica fume cement concrete specimens cured by water-ponding is depicted in Fig. 7. The drying shrinkage strain, as measured by five pairs of demec gauges, increased with the time of exposure to ambient environment. Further, the drying shrinkage in the silica fume cement concrete specimens was more than that in the plain cement concrete specimens. The average drying shrinkage strain after 180 days of exposure to the ambient conditions was

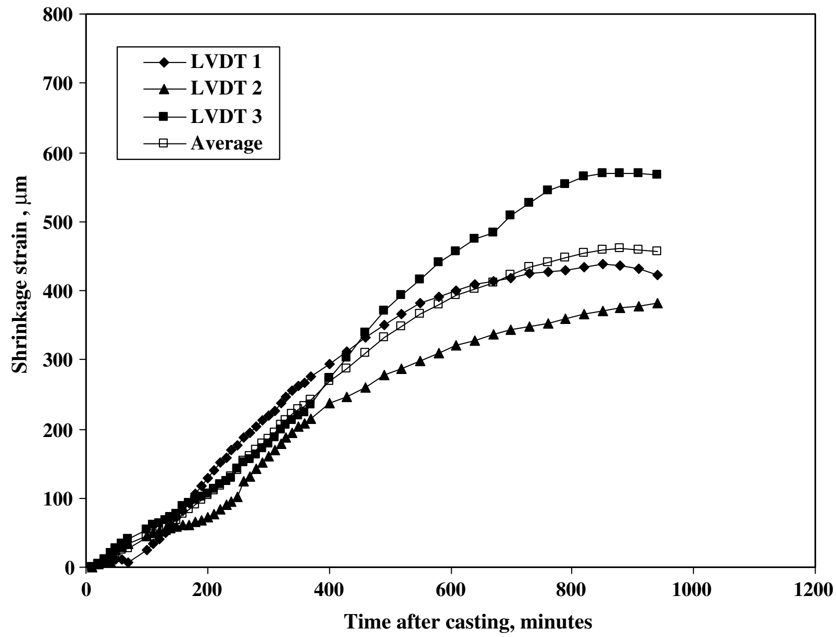

Fig. 4. Typical plot of plastic shrinkage strain in 5 × 5 m plain cement concrete specimens.

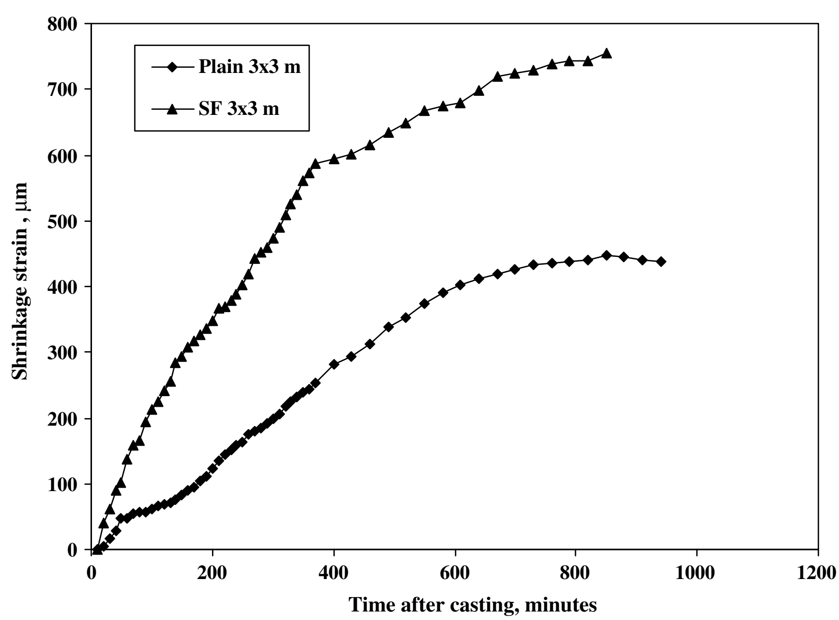

Fig. 5. Average plastic shrinkage strain in 3 × 3 m plain and silica fume cement concrete specimens.

578 µm in the plain cement concrete specimens while it was 820 µm in the silica fume cement concrete specimens.

As shown in Fig. 8, the data on drying shrinkage strain in the 5 × 5 m plain and silica fume cement concrete specimens cured by covering with wet-burlap also indicated a trend similar to that noted in Fig. 7. After 180 days of exposure to the ambient environment, the drying shrinkage strain was 707 µm in the plain cement concrete specimens while it was 877 µm in the silica fume cement concrete specimens.

Fig. 9 depicts the drying shrinkage strain in the 3 × 3 m plain and silica fume cement concrete specimens cured by water-ponding. As expected, the drying shrinkage strain increased with time in both types of concrete specimens. However, the drying shrinkage strain in the silica fume cement concrete specimen was more than that in the plain cement concrete specimen. After 180 days of exposure to the ambient conditions, the drying shrinkage strain in the plain and silica fume cement concrete specimens was 520 and 832 µm, respectively. The drying shrinkage strain in the plain and silica fume cement concrete specimens cured by covering them with wet-burlap are depicted in Fig. 10. These data also indicate a trend similar to that noted in Fig. 9. The drying shrinkage strain in the plain and silica

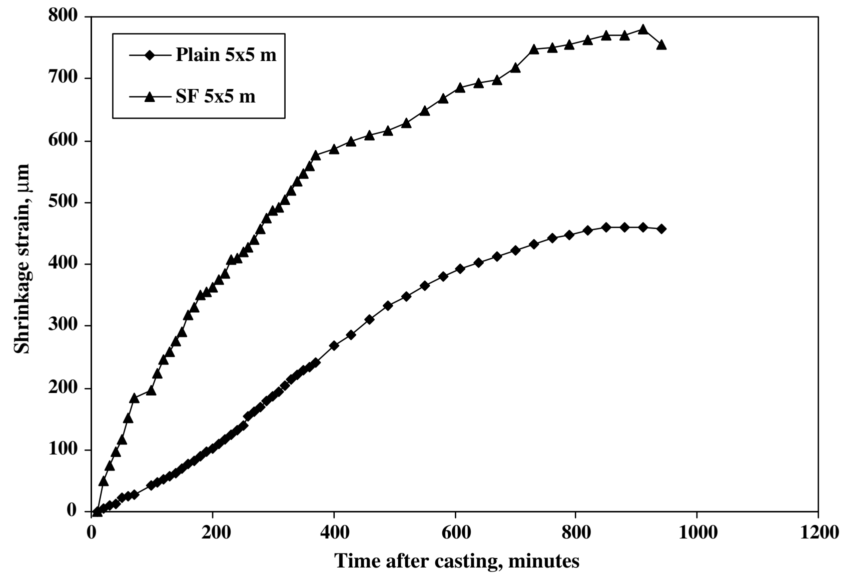

Fig. 6. Average plastic shrinkage strain in 5 × 5 m plain and silica fume cement concrete specimens.

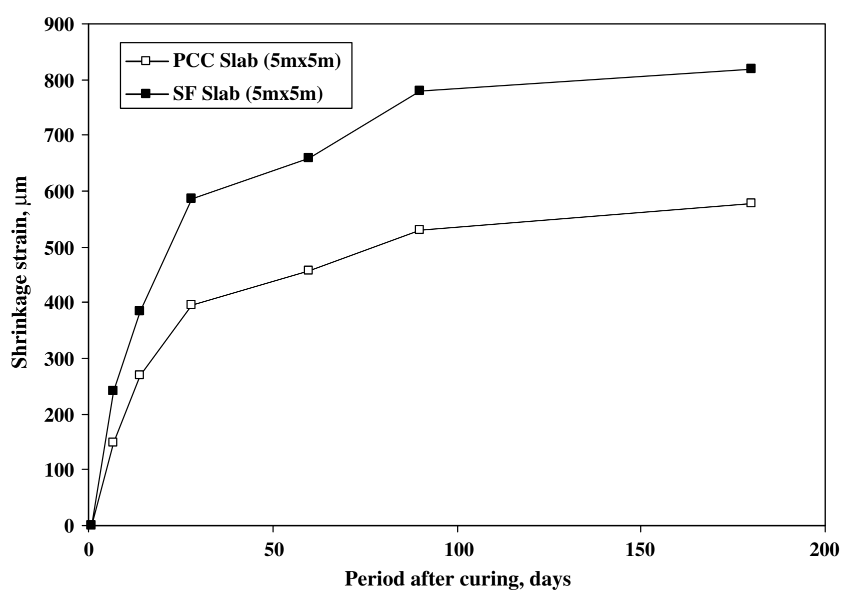

Fig. 7. Average drying shrinkage strain in plain and silica fume cement concrete specimens (5 m × 5 m) cured by water-ponding.

fume cement concrete specimens, after 180 days of exposure, was 546 and 840 µm, respectively.

Comparison of data in Figs. 7–10 indicates that drying shrinkage in the plain and silica fume cement concrete specimens cured by water-ponding was less than that in the concrete specimens cured by covering with wet-burlap. Further, the drying shrinkage strain in the big (5 × 5 m) concrete specimens, both plain and silica fume cement concretes, was more than that in the small (3 × 3 m) concrete specimens.

3.3. Properties of cylindrical concrete specimens

The pulse velocity, compressive strength and split tensile strength of plain cement concrete cylinders cured by water-ponding is summarized in Table 1. These properties increased with the time of curing. The major increase was noted during the initial 28 days. Thereafter, the increase was relatively marginal. After 180 days of curing, the pulse velocity, compressive strength and the split tensile strength were 4655 m/s, 41 MPa, and 4.0 MPa, respectively. The compressive strength, pulse velocity and split tensile strength of plain cement concrete specimens cured by covering them with wet-burlap are summarized in Table 2. These properties also increased with age. After 180 days of curing, the compressive strength, pulse velocity and split tensile strength were 39.5 MPa, 4576 m/s and 3.88 MPa, respectively.

The compressive strength, pulse velocity and split tensile strength of silica fume cement concrete specimens cured by

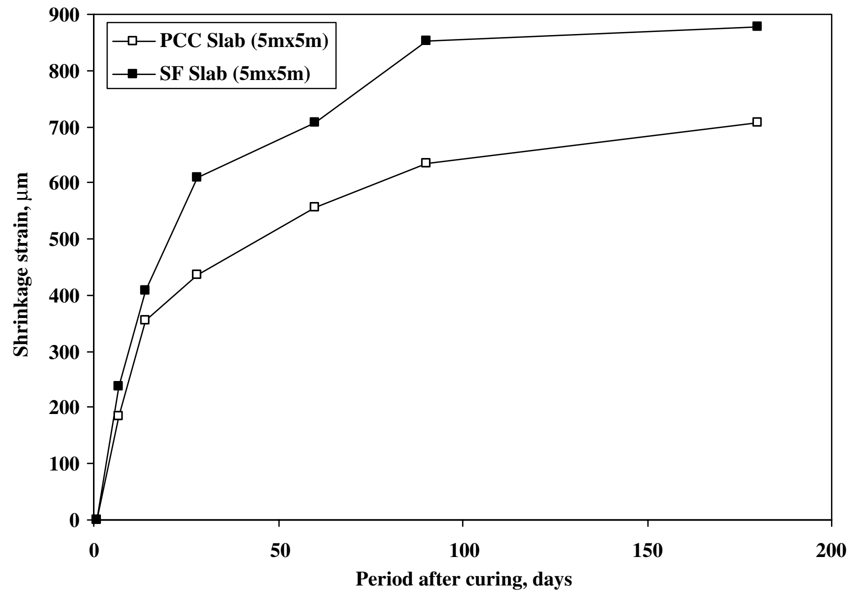

Fig. 8. Average drying shrinkage strain in plain and silica fume cement concrete specimens (5 m × 5 m) cured by covering them with wet burlap.

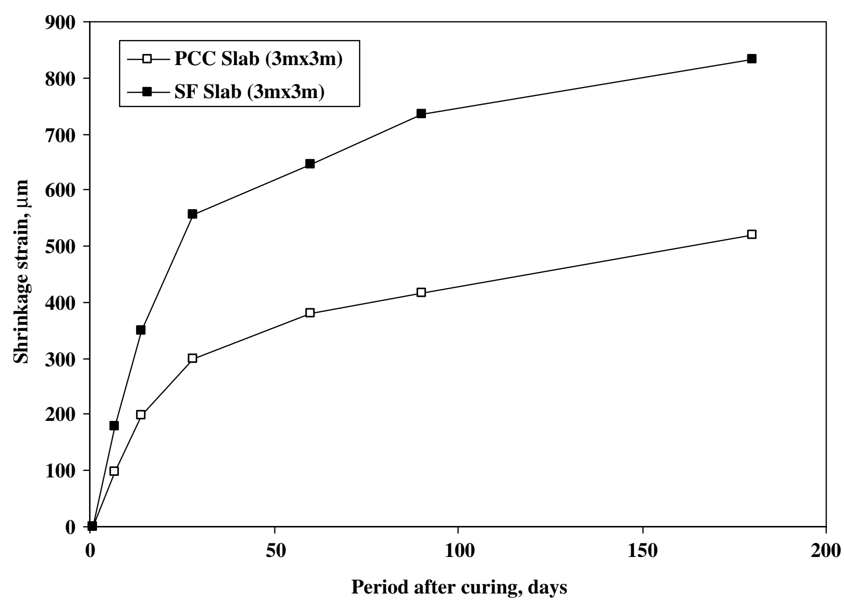

Fig. 9. Average drying shrinkage strain in plain and silica fume cement concrete specimens (3 m × 3 m) cured by water-ponding.

water-ponding are summarized in Table 3. As expected these values increased with the period of curing. After 180 days of curing, the compressive strength, pulse velocity and split tensile strength were 53.4 MPa, 4830 m/s, and 4.90 MPa, respectively. Table 4 shows the compressive strength, pulse velocity and split tensile strength of silica fume cement concrete specimens cured by covering them with wet-burlap. These values also increased with the period of curing. After 180 days of curing, the compressive strength, pulse velocity and split tensile strength were 52.4 MPa, 4798 m/s and 4.76 MPa, respectively.

The data on pulse velocity, compressive strength and split tensile strength, shown in Tables 1–4, indicate that these properties of concrete specimens cured by water-ponding were better than those cured by covering them with wet-burlap. This is true for both the plain and silica fume cement concrete specimens.

The pulse velocity, compressive strength and tensile strength of silica fume cement concrete specimens were more than those of plain cement concrete specimens. However, the improvement in the compressive strength due to the use of silica fume was higher than tensile strength and pulse velocity (30% as compared with 22% and 3.8%, respectively, for the specimens cured by water-ponding). The superior performance of silica fume cement concrete may be ascribed to its dense microstructure that has

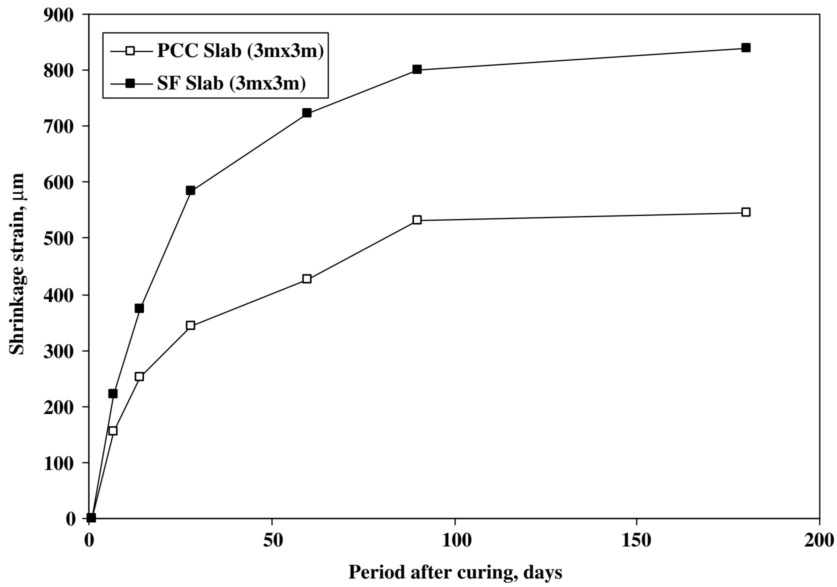

Fig. 10. Average drying shrinkage strain in plain and silica fume cement concrete specimens (3 m × 3 m) cured by covering them with wet-burlap.

Table 1
Compressive and split tensile strength and pulse velocity of plain cement concrete specimens cured by water-ponding

Period of curing (days)	Compressive strength (MPa)	Split tensile strength (MPa)	Pulse velocity (m/s)
3	28.1	2.08	4245
7	33.1	2.74	4405
14	37.8	3.34	4511
28	40.0	3.78	4592
90	40.8	3.99	4644
180	41.0	4.01	4655

Table 2
Compressive and split tensile strength and pulse velocity of plain cement concrete specimens cured by covering with wet-burlap

Period of curing (days)	Compressive strength (MPa)	Split tensile strength (MPa)	Pulse velocity (m/s)
3	27.7	1.88	4207
7	30.3	2.23	4345
14	34.2	3.07	4442
28	38.5	3.74	4549
90	39.4	3.90	4562
180	39.5	3.88	4576

Table 3
Compressive and split tensile strength and pulse velocity of silica fume cement concrete specimens cured by water-ponding

Period of curing (days)	Compressive strength (MPa)	Split tensile strength (MPa)	Pulse velocity (m/s)
3	28.7	2.03	4266
7	34.2	2.92	4410
14	37.6	3.89	4568
28	48.5	4.65	4746
90	52.8	4.84	4822
180	53.4	4.90	4830

Table 4
Compressive and split tensile strength and pulse velocity of silica fume cement concrete specimens cured by covering with wet-burlap

Period of curing (days)	Compressive strength (MPa)	Split tensile strength (MPa)	Pulse velocity (m/s)
3	26.8	2.01	4293
7	33.4	2.71	4420
14	39.1	3.69	4530
28	49.3	4.64	4688
90	51.1	4.75	4769
180	52.4	4.76	4798

been further improved by the extended curing period of 21 days.

4. Discussion

4.1. Plastic and drying shrinkage and concrete performance

The data developed in this field study indicate that both the plastic and drying shrinkage strain in the silica fume cement concrete specimens was more than that in the plain cement concrete specimens. However, cracks were not noted in these specimens, irrespective of their dimensions. The plastic shrinkage strain in the silica fume cement concrete specimens was on an average 69% more than that in the plain cement concrete specimens. The increased plastic shrinkage strain in the silica fume cement concrete specimens over plain cement concrete specimens has also been reported earlier [5–10]. Almusallam et al. [5] investigated plastic shrinkage cracking in $450 \times 450 \times 20$ mm blended cement concrete specimens that included silica fume at dosages of 5%, 10%, and 15%. These specimens were exposed to hot-humid and hot-dry environments. The rate of water evaporation and bleeding was monitored in these specimens. The measurement of these two parameters indicated an increased plastic shrinkage cracking in silica fume and other blended cement concretes as compared to plain cement concrete.

Al-Amoudi et al. [6] have recently evaluated the effect of source and dosage of silica fume on plastic shrinkage of concrete exposed to hot weather conditions. The authors reported that the plastic shrinkage strain increased with increasing dosage of silica fume (5%, 7.5% and 10% by weight of cement) irrespective of the type of silica fume used [6]. Plastic shrinkage strain in all the silica fume cement concretes was more than that in the plain cement concrete. The highest plastic shrinkage strain was noted in undensified silica fume cement concrete. This was attributed to the undensified nature (i.e., lower bulk density) and higher specific surface area of this silica fume compared to the other four densified silica fume samples. Physical properties of the silica fume, such as fineness, as represented by the specific surface area, bulk density and microscopic properties, such as average pore radius and the total pore volume, were correlated against the maximum values of plastic shrinkage strain. No relationship was noticed between microscopic properties and the maximum plastic shrinkage strains, while a definite relationship was observed between the plastic shrinkage strain and the fineness of the silica fume.

Free- and restrained-shrinkage of concretes with and without silica fume were studied by Bloom and Bentur [7]. A special uniaxial restraining rig was developed in which the stress required to prevent shrinkage from occurring could be monitored. Variables studied were the water–cement ratio, influence of silica fume, and exposure conditions (either exposure to drying environment immediately after casting or immediate sealing of the concrete after casting). The presence of silica fume increased free plastic shrinkage of the concrete and led to earlier cracking than a similar low-water/cement concrete (0.33) with no silica fume. The sealed low-water-binder ratio concretes (0.33) developed considerable restraining (residual) stress, but none of them cracked. This stress was higher in the silica fume cement concrete.

The increased plastic shrinkage strain in the silica fume cement concrete specimens may be attributed to the low bleeding that this type of blended cement always exhibits. The absence of bleed water in the fresh silica fume cement concrete enhances the evaporation of pore water from the surfacial concrete layers under hot weather. The evaporation of mix water from fresh concrete induces shrinkage stress in it. If these strains exceed the tensile strain capacity of concrete, it will crack [8–10].

In the case of plain cement concrete specimens, there is always some bleed water and, therefore, this water will evaporate first if hot weather conditions prevail. Once all the bleeding water evaporates, pore water from fresh concrete will then start evaporating. Such a delay in the evaporation of pore water will enhance the strength development of hardening concrete thereby resisting the tensile stresses induced by the ambient conditions. As such, plain cement concrete will resist cracking more than silica fume cement concrete.

Eventhough the plastic shrinkage strain in the silica fume cement concrete specimens was more than that in the plain cement concrete specimens, they were not high enough to cause cracking. In a previous investigation [6], a threshold value of plastic shrinkage strain that could result in cracking was reported to be around 1100 μm. The plastic shrinkage strain in the silica fume cement concrete specimens was less than 800 μm. The low shrinkage values could be attributed to the properties of the silica fume utilized in the preparation of concrete specimens. The rate of bleeding of the selected silica fume cement concrete was not very low; commensurate with the rate of evaporation leading to plastic shrinkage that produced strains less than the threshold value of 1100 μm.

Another reason for the absence of cracks in the silica fume cement concrete is its high tensile strength. The high tensile strength of silica fume cement concrete may be attributed to the good pozzolanic reactivity of the selected silica fume and the extended period, i.e., 21 days, of curing. The importance of good and extended curing has been emphasized by several researchers. Whitting et al. [11] presented the results of a study of the cracking tendency and drying shrinkage of silica fume cement concretes. The results indicated that the tendency of concrete to crack was influenced by the addition of silica fume only when concrete was improperly cured. When the concrete was cured for seven days under continuously moist conditions, there was no significant effect of silica fume on the tendency of the concrete to exhibit early-age cracking. The long-term shrinkage of plain and silica fume cement concretes was almost similar. At early ages, however, silica fume cement concrete showed somewhat higher shrinkage than the plain cement concrete. It was suggested that specifications for silica fume concretes in bridge deck construction include a provision for seven days continuous moist curing of exposed surfaces. El-Hindy et al. [12] reported that the drying shrinkage of silica fume cement concrete decreased with the period of curing. Hooton [13] reported that the drying shrinkage of silica fume cement concrete was 10–22% more than that of normal Portland cement concrete of same water/binder ratio and same binder content. According to Khatri and Sirivivatnanon [14] the early drying shrinkage of concrete was more than that of plain cement concrete. However, the long-term drying shrinkage of the former cement was less than that of the latter.

The drying shrinkage in both the plain and silica fume cement concrete specimens cured by covering them with wet-burlap was more than that of similar concrete specimens cured by water-ponding. Further, the drying shrinkage of big specimens, both plain and silica fume cement concretes, was more than that of small concrete specimens. However, the difference in the shrinkage strains in the big and small concrete specimens was marginal. The drying shrinkage in the silica fume cement concrete specimens, both small and big, was more than that in the similar plain cement concrete specimens.

In the concrete specimens cured by water-ponding, the evaporation of mixing water is minimized thereby increasing the strength more than that of specimens cured by covering with wet-burlap. Curing concrete specimens by wetting two times a day with wet-burlap will not totally stop the evaporation of the mixing water as a result the hydration and strength gain will be hampered. Since these concrete specimens were cast during summer, our observations indicated that water would evaporate from the wet-burlap within about 10 min thereby influencing the hydration reactions.

The higher drying shrinkage in the big (5×5 m) cement concrete specimens, prepared with both plain and silica fume cements, is ascribed to the larger surface area of these specimens. However, the difference in the drying shrinkage strain in the big and small concrete specimens was marginal. It should also be noted that such a difference in the drying shrinkage strain in plain and silica fume cement concrete specimens, whether cured by water-ponding or covering them with wet burlap, was marginal.

The data developed in this study indicate that the major factor that affects the drying shrinkage strain is the type of cement. For example, the drying shrinkage in the big plain and silica fume cement concrete specimens cured by water-ponding was 578 and 820 μm, respectively, with a 42% increase in the silica fume cement concrete. In the big concrete specimens cured by covering them with wet-burlap, the drying shrinkage in the silica fume cement concrete specimens increased by 24%. The increase in the drying shrinkage strain in the small silica fume cement concrete specimens, cured by water-ponding, was 60%. In the concrete specimens cured by covering with wet-burlap, the increase was 53% in the silica fume cement concrete as compared with the plain cement concrete.

The higher drying shrinkage of both the big and small silica fume cement concrete specimens may be ascribed to the self-desiccation and autogenous shrinkage of this very fine material and the lack of sufficient water in the dense microstructure of silica fume blended cement paste. Hooton [13] reported that concrete with lower percentage of silica fume has not shown much increase in shrinkage, whereas concrete with higher percentage replacements of silica fume exhibited considerable increase in shrinkage.

Another point to be discussed is the results of this study and the field observations. Several cases of cracking of silica fume cement concrete elements cast under hot weather conditions have been reported. The specimens utilized in this study were prepared to be as representative as possible to the actual field conditions and they were prepared during summer. The absence of cracks could be attributed to the good quality of the silica fume utilized, concrete mix design and above all good curing. The other cause could be the variation in the restraint in the experimental and the actual field conditions. The field structures normally have a complex geometry and heavy reinforcement. These conditions may provide more restraint than that experienced by the experimental specimens. Whatever be the disparities between the field and experimental conditions, the data developed in this study have re-emphasized the importance of selecting a good quality silica fume and early and extended period of curing, if cracking is to avoided under hot weather conditions.

4.2. Specimen dimensions and curing regime

One of the objectives of this study was to evaluate the effect of specimen dimensions and curing regime on plastic and drying shrinkage of plain and silica fume cement concretes. The data indicated that both plastic and drying shrinkage strains increased with the size of the specimens. However, the effect of specimen size on both the plastic and drying shrinkage was not significantly high.

The plastic and drying shrinkage strains in the plain and silica fume cement concrete specimens cured by covering them with wet-burlap were more than those in the concrete specimens cured by water-ponding. Therefore, curing by water-ponding is preferable. Continuous wet-curing by water-ponding for 14 days followed by wet-burlap curing for another seven days is recommended under hot weather conditions, particularly for silica fume cement concrete specimens.

5. Conclusions

A field study was conducted to assess the effect of curing methods and specimen size on the plastic and drying shrinkage strain in plain and silica fume cement concretes. From the data developed in this study, the following conclusions could be drawn.

The plastic shrinkage strain was primarily affected by the type of cement. Plastic shrinkage strain in the silica fume cement concrete specimens was more than that in the plain cement concrete specimens. The plastic shrinkage strain in the silica fume cement concrete specimens was on an average 70% more than that in the plain cement concrete specimens. This trend was noted in both the small and big concrete specimens. However, the plastic shrinkage strain was not significantly affected by the specimen size.

The drying shrinkage strain in both the plain and silica fume cement concrete specimens cured by covering with wet burlap was more than that in similar concrete specimens cured by water-ponding. Furthermore, the drying shrinkage of the big specimens, prepared with both plain and silica fume cement concretes, was more than that in the small specimens. However, the difference in the drying shrinkage strains in the big and small concrete specimens was marginal. The drying shrinkage strains in the silica fume cement concrete specimens, both small and big, was more than those in the plain cement concrete specimens.

As expected, the compressive strength, split tensile strength, and pulse velocity increased with age. These values were more in the silica fume cement concrete than in the plain cement concrete. The compressive strength, split tensile strength, and pulse velocity of specimens cured by water-ponding were more than those of the concrete specimens cured by covering them with wet-burlap. This trend was noted in both the plain and silica fume cement concretes.

The improvement due to the use of silica fume was more in the compressive strength than in the split tensile strength and pulse velocity. The superior performance of silica fume cement concrete, over plain cement concrete, may be ascribed to its dense microstructure and the extended period of curing, 21 days, compared with seven days for plain cement concrete.

The high tensile strength of the silica fume cement concrete was probably helpful in preventing the development of shrinkage cracks, even though the shrinkage strain in these concrete specimens was more than that in the plain cement concrete specimens.

References

[1] Al-Amoudi OSB, Almusallam AA, Khan MM, Maslehuddin M. Effect of hot weather on compressive strength of plain and blended cement mortars. In: Proceedings of the 4th Saudi engineering conference, King Abdulaziz University Jeddah; 1995: vol. 2, p. 193–9.

[2] Al-Amoudi OSB, Rasheeduzzafar, Maslehuddin M, Abduljauwad SN. Influence of sulfate ions on chloride-induced reinforcement corrosion in plain and blended cement concretes. Cem Concr Aggre 1994;16(1):3–11.

[3] Al-Amoudi OSB, Maslehuddin M, Bader MA. Characteristics of silica fume and its impact on concrete in the Arabian Gulf. Concr Construc 2001;35(2):45–50.

[4] Cohen MD, Olek J, Dolch WL. Mechanism of plastic shrinkage cracking in portland cement and portland-cement-silica fume paste and mortar. Cem Concr Res 1990;20(1):103–19.

[5] Almusallam AA, Maslehuddin M, Abdul-Waris M, Dakhil FH, Al-Amoudi OSB. Plastic shrinkage cracking of blended cement concretes in hot environments. Mag Concr Res 1999;51(4):241–6.

[6] Al-Amoudi OSB, Maslehuddin M, Abiola TO. Effect of type and dosage of silica fume on plastic shrinkage in concrete exposed to hot weather. Construc Build Mater 2004;18:737–43.

[7] Bloom R, Bentur A. Free and restrained-shrinkage of normal and high-strength concrete. ACI Mater J 1995;92(2):211–7.

[8] Uno PJ. Plastic shrinkage cracking and evaporation formulas. ACI Mater J 1998;95(4):365–75.

[9] Radocea A. A model of plastic shrinkage. Mag Concr Res 1994;46(167):125–32.

[10] Holt E, Leivo M. Cracking risks associated with early age shrinkage. Cem Concr Compos 2004;26:521–30.

[11] Whiting DA, Detwiler RJ, Lagergen ES. Cracking tendency and drying shrinkage of silica fume concrete for bridge deck applications. ACI Mater J 2000;97(6):71–7.

[12] El-Hindy E, Miao BO, Chaallal O, Aitcin PC. Drying shrinkage of ready mixed high-performance concrete. ACI Mater J 1994;91:300.

[13] Hooton RD. Influence of silica fume replacement of cement on physical properties and resistance to sulfate attack, freezing and thawing, and alkali–silica reactivity. ACI Mater J 1993;90:143.

[14] Khatri RP, Sirivivatnanon V. Effect of different supplementary cementitous materials on mechanical properties of high performance concrete. Cem Concr Res 1995;25(1):209–20.