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Long-term drying shrinkage of mortar — influence of silica fume and size of fine aggregate

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Abstract

In this paper, an experimental investigation on the effect of silica fume and size of aggregate on the long-term drying shrinkage of mortar is reported. Silica fume was used as a partial replacement by weight of cement from 0% to 30%. The maximum size of fine aggregate was 1.18 and 2.36 mm, respectively, in series I and II mortar mixes. The water–cementitious material ratio and the cementitious material–sand ratio were 0.50 and 1:3. The ultimate drying shrinkage was measured up to the age of 1095 days. From the experimental test results, it was observed that the addition of silica fume has a significant influence on the drying shrinkage at early ages of mortar. It increases with increase in silica fume content. This increase in early days drying shrinkage is due mainly to very high pozzolanic reaction and pore size refinement mechanism of silica fume. The drying shrinkage in mortars with higher contents of silica fume was observed to be as high as 7–10 times greater than that observed in mortars without silica fume at early days. No significant influence of silica fume was found on the long-term drying shrinkage of mortar. Furthermore, it has been dramatically observed that the long-term drying shrinkage of mortar decreases with the increase in the size of fine aggregate. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Shrinkage is a common phenomenon generally encountered in almost every cementitious product due to contraction of total mass upon loss of moisture. Though it is a multidimensional contraction, the drying shrinkage of concrete is normally measured in the largest dimension of the body. The total drying shrinkage of concrete can be contributed from various forms of shrinkage taking place in the concrete. When a cementitious product is still in plastic stage the primary form of shrinkage, normally termed as plastic shrinkage, occurs due to the evaporation of bleeding water. Autogenous shrinkage or self-desiccation shrinkage occurs during the hydration of cement. The investigations made by Jensen and Hansen [1] revealed that the addition of silica fume markedly increases the autogenous shrinkage. This is due to the formation of cohesive and adhesive solids as a result of chemical reaction between cement and water wherein the volume of the end product is lesser than the initial volume of the constituents. Early stage chemical shrinkage of cement pastes has been studied [2] with w/c ratios, 0.30 and 0.375, which experienced a value of shrinkage of 0.7% and 1.0%, respectively. The CaO present in cementitious material produces $Ca(OH)_2$, during hydration of cement, which acts as a source of alkalinity. This alkalinity is gradually destroyed by CO_2 in the form of carbonation shrinkage [3]. Thermal shrinkage takes place when high temperatures prevail at the time of setting. The total drying shrinkage depends upon various parameters such as density, chemical composition, water–cementitious material ratio, relative humidity, duration of curing, type and size of aggregate, aggregate content, size and shape of the member, type of exposure, etc. The presence of filler materials such as fly ash or sand ultimately results in very significant reduction of total shrinkage. The drying shrinkage of cementitious members increases with increase in the surface area to volume ratio [4,5]. Use of industrial based by-products has attracted considerable attention in concrete technology since the beginning of the twentieth century. The main reason for this development is that most of the industrial by-products are composed of similar oxides as in

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the ordinary Portland cement but in different mineralogical forms. Silica fume, a by-product from silicon alloy or Ferro silicon alloy, rich in SiO_2 content is a highly pozzolanic material. The addition of silica fume changes the orientation of CH crystals and modifies the properties of C-S-H gel [6,7]. In the expansive cement pastes, the presence of silica fume decreases the expansion characteristics [8]. Due to shrinkage stresses developed in the vicinity of CH crystals, the cement pastes undergo microcracking [9]. The effect of mineral admixtures on creep and shrinkage of cement pastes has been studied [10]. The creep and shrinkage are promoted due to decrease in spacing of C-S-H particles, changes in interlayer spacing, micro shearing of C-S-H sheets, changes in chemical bonding, surface diffusion of solid material and changes in disjoining pressure.

Increase in volume content of aggregate and curing time and decrease in water–cement ratio resulted in the decrease of ultimate drying shrinkage [5,11]. In more recent times, various changes have taken place in concrete research. One of them is the evolution of high-performance concrete in which use of lower w/c ratio and higher quantities of cementitious materials with high-range water-reducing agents (HRWRA) is inevitable. Even though it improves the strength very significantly in the early days, it appears to have the development of cracks during hardening. High-strength concrete containing silica fume experience severe plastic shrinkage cracking [12,13]. The plastic-cracking behavior of normal-strength concrete mixes is much less severe than that of high-strength concrete mixes. Therefore, significant research efforts are being diverted towards understanding the long-term drying shrinkage of high-strength cementitious materials. It has been recently observed that the long-term drying shrinkage of low-strength concrete is greater and smaller for medium- and high-strength concrete [14,15]. Longer moist curing is effective in reducing the drying of moisture from concrete [16]. El Hindy et al. [17] have reported that the longer curing time and the lower water–cementitious material ratio reduce the drying shrinkage of ready mixed concrete with silica fume. The comparison of drying of concrete in the laboratory and field conditions revealed that the laboratory small specimens overestimate the shrinkage of high-performance concrete in real structures [18]. Improper curing of high-strength concrete at early days results in significant strength loss and increase in drying shrinkage at later age, when exposed to drying ambient conditions irrespective of composition of concrete [19]. However, concrete containing 5% and 10% silica fume exhibited a substantial reduction of strength loss and drying shrinkage. Buil et al. [20] observed a slight increase of the shrinkage of mortar containing silica fume, but a higher value of shrinkage was observed with the addition of superplasticizer alone. Long-term strength losses of concrete containing silica fume are linked to the structural effects of drying [21]. Hooton [22] performed drying shrinkage tests on concrete containing silica fume. It was observed that concrete with lower percentage of silica fume has not shown much increase in shrinkage, whereas concrete with higher percentage replacements exhibited considerable increase in shrinkage.

2. Experimental program

2.1. Materials

2.1.1. Cement

An ordinary Portland cement, readily available commercially, was adopted throughout for performing the present research program. The properties of the cement are shown in Table 1.

2.1.2. Silica fume

Silica fume obtained from an electric arc furnace in the manufacturing of Ferro silicon alloy with the following chemical composition as shown in Table 2 was used. The silica fume was used as a partial replacement of cement in the mortar mixes. In series I mortar mixes, the amount of silica fume was incorporated from 0 to 30 wt.% of cement at a constant increment of 2.5%, whereas in series II mortar mixes, it was 0, 10, 15 and 20 wt.%. Specific gravity and specific surface of the silica fume are 2.051 and 16,000 m^2/kg, respectively.

2.1.3. Sand

Natural river sand available in the nearby, was adopted with the fractions of sand passing through 1.18 mm sieve and retaining on 0.60 mm in the series I mixes. Whereas in series II mortar mixes, the sand fractions falling in the ranges 2.36–1.18, 1.18–0.60 and 0.60–0.30 mm were used at 1:1:1 ratio. The specific gravity and the bulk density of sand are 2.68 and 1584 kg/m^3, respectively.

2.2. Mix proportions

1. In series I mortar mixes, the silica fume was used as a cement replacement material at 0, 5, 10, 15, 17.5, 20,

Table 1
Physical properties of cement

Property	Result
Fineness of cement (%)	2.65
Normal consistency (%)	31.5
Setting times (min)	
(a) Initial	135
(b) Final	335
Specific gravity	3.168
Compressive strength (MPa)	
(a) 3 days	21.00
(b) 7 days	30.00
(c) 28 days	49.00

Table 2
Chemical composition of silica fume

Chemical compound	Result (%)
Silica (SiO_2)	84.0–86.0
Alumina oxide (Al_2O_3)	1.0 (max)
Iron oxide (Fe_2O_3)	2.0–3.5
Silica + alumina + iron oxide ($SiO_2 + Al_2O_3 + Fe_2O_3$)	87–90.5
Calcium oxide (CaO)	1.0–1.5
Loss on ignition	4–7

22.5, 25, 27.5 and 30 wt.% of cement. Whereas in series II mortar mixes, the replacements were 0, 10, 15 and 20 wt.%.

2. The cementitious material–sand ratio was 1:3.
3. The water–cementitious (cement + silica fume) material ratio was 0.5.

2.3. Specimen size and preparation

Bar moulds of size 25 × 25 × 250 mm were used to prepare mortar specimens. The mortar mix with the required proportions are mixed and compacted by hand operations. Gauge studs were inserted in the bar moulds coaxial with the bar before the mortar was poured in to the moulds.

2.4. Curing of specimens

After 24 h, the mortar bar specimens were demoulded and subsequently submerged in water for curing for 7 days. Lengths of the specimens were measured using a length comparator immediately after curing.

2.5. Exposure and testing of specimens

Soon after measuring the initial length, the specimens were exposed to the laboratory environment. The average temperature in the laboratory was 33 ± 2°C and the relative humidity was 65 ± 5%. The lengths of exposed specimens were measured for change in length and for drying shrinkage at different ages. The drying shrinkage of mortar was the contraction in the length of mortar bar expressed as percentage. The drying shrinkage of mortar was measured at different ages of 28, 400, 620, 730 and 1095 days in the series I mortar mixes. In series II mortar mixes, the observations were made at the ages of 28, 60, 120, 180, 365 and 730 days.

3. Test results and discussion

Drying shrinkage of cement mortars containing silica fume has been measured. The main intention of this experimental work was to study the influence of silica fume and size of aggregate on the drying shrinkage of mortar. Series I mortar mixes were made with 0–30% silica fume and 1.18 mm maximum size of fine aggregate. Series II mortar mixes contain 0–20% of silica fume and 2.36 mm maximum size of fine aggregate. The experiments performed, however, indicate that the addition of silica fume has a dominating influence on the 28 days drying shrinkage. As shown in Tables 3 and 4, the drying shrinkage of mortar at 28 days increases with the increase in silica fume content. The increase in drying shrinkage is evidently supported by the literature [20–22]. The observed percentage drying shrinkage at 28 days was 0.083 in the series I mortar mixes (CMSF9) with 30% addition of silica fume, whereas in series II mortar mixes, the highest value of 0.0907 occurred (CSFM3) at 20% silica fume content. The corresponding drying shrinkage values are 0.011 and 0.00757, respectively in series I and II mortar mixes (CMSF0 and CSFM0) without silica fume, respectively. The increase in the drying shrinkage of mortar might be due mainly to pozzolanic reaction and pore size refinement mechanism of silica fume. The early stage chemical shrinkage due to pozzolanic reaction is supported by the experimental work done on cement paste [2]. Autogenous shrinkage or self-desiccation shrinkage might be the result of refinement of pore size due

Table 3
Drying shrinkage of series I mortars mixes at different ages

		Drying shrinkage at different ages (%)				
Mix designation	Addition of silica fume (%)	28 days	400 days	620 days	730 days	1095 days
CMSFO	0.00	0.011	0.210	0.537	0.630	0.764
CMSF1	5.00	0.019	0.216	0.539	0.662	0.804
CMSF2	10.00	0.030	0.217	0.552	0.710	0.814
CMSF3	15.00	0.034	0.222	0.569	0.724	0.838
CMSF4	17.50	0.049	0.231	0.579	0.734	0.857
CMSF5	20.00	0.061	0.242	0.582	0.699	0.859
CMSF6	22.50	0.064	0.253	0.587	0.685	0.820
CMSF7	25.00	0.072	0.274	0.598	0.636	0.833
CMSF8	27.50	0.076	0.281	0.602	0.655	0.821
CMSF9	30.00	0.083	0.289	0.624	0.691	0.805

Table 4
Drying shrinkage of series II mortars mixes at different ages (days)

Mix designation	Addition of silica fume (%)	Drying shrinkage at different ages (%)					
		28 days	60 days	120 days	180 days	365 days	730 days
CSFMO	0	0.00757	0.0114	0.053	0.151	0.212	0.190
CSFM1	10	0.0303	0.0756	0.113	0.205	0.271	0.378
CSFM2	15	0.0812	0.103	0.268	0.306	0.419	0.460
CSFM3	20	0.0907	0.113	0.132	0.151	0.302	0.227

to which cohesive and adhesive solids are formed during the reaction of $Ca(OH)_2$ and SiO_2.

Tables 3 and 4 show the influence of silica fume on the long-term drying shrinkage of series I and II mortar mixes, respectively. In series I mortar mixes, the shrinkage has been measured at the age of 400, 620, 730 and 1095 days. At the age of 400 days, the ultimate drying shrinkage in series I mortar mixes (CMSF0 and CSFM9) was ranged between 0.210% and 0.289% corresponding to 0% and 30% addition of silica fume, respectively. In-between these limits, the drying shrinkage of mortar increases with increase in the silica fume content. At the age of 620 days, the ultimate drying shrinkage was observed between 0.537% and 0.624% at 0% and 30% addition of silica fume, respectively. Similar variation has been observed at the age of 620 days also. At the age of 730 days, the highest ultimate drying shrinkage was observed in mortar mixes (CMSF4) with 17.50% silica fume. The corresponding value of ultimate drying shrinkage was 0.734%. At the age of 730 days, all the mortar mixes, except pure cement mortar, containing silica fume have exhibited increase in the drying shrinkage. However, the highest value was not observed in mortars incorporated with higher quantities of silica fume as has been shown in Table 3. The drying shrinkage of pure cement mortar (CMSF0) was 0.630%. As shown in Table 3, the highest values of drying shrinkage at the age 1095 days occurred in mortars containing silica fume between 17.50% and 20.00% (CMSF4 and CMSF5). In the mortar mixes with 17.50% and 20.00% addition of silica fume, the highest values of drying shrinkage were 0.857% and 0.859%, respectively. In contrast with the results obtained at the ages of 400 and 620 days, the ultimate drying shrinkage at the age of 730 and 1095 days in series I mortar mixes does not increase with increase in the silica fume content. However, the highest values were observed with silica fume between 17.50% and 20.00%. The drying shrinkage values shown in Table 3 occurred using the maximum fine aggregate size of 1.18 mm.

The drying shrinkage of series II mortar mixes increases with increase in the silica fume content at the age of 28 days. As has been shown in Table 4, the drying shrinkage of mortar increases with increase in the silica fume content up to 15% and 20% silica fume content has resulted in reduction of drying shrinkage at all ages of mortar. From the experimental test results, it was clear that the 15% addition of silica fume in the mortar mixes (CSFM2) exhibit highest ultimate long-term drying shrinkage. At the age of 365 days (1 year), the highest value of drying shrinkage was 0.419%. In series II mortar mixes, at the age of 730 days (2 years), the highest value of drying shrinkage was observed to be 0.460% at 15% silica fume. It is also clear from Table 4 that the drying shrinkage has increased from 0.419% to 0.460% at the age of 365 and 730 days, respectively. Between 180 and 365 days, the drying shrinkage has increased from 0.306% to 0.419%. This shows that the rate of increase in the drying shrinkage of series II mortar mixes decreases with the age of mortar. Small variations in the ultimate drying shrinkage was observed in series I and II mortar mixes at the same silica fume content at the age of 28 days. Comparison of shrinkage, at the age of 730 days, of mortar in series I and series II has indicated a significant reduction in the drying shrinkage of series II mortar mixes. The ultimate drying shrinkage of mortar, comparing Tables 3 and 4, significantly decreases with the addition of larger size fine aggregate. At 15% silica fume content, at the age of 730 days, the ultimate drying shrinkage values are 0.724 and 0.460%, respectively, in series I and II mortar mixes (CMSF3 and CSFM2). That is, series I mortar mixes with 1.18 mm fine aggregate size has exhibited drying shrinkage values almost double the values observed in series II mortar mixes. The drying shrinkage tests on mortars containing silica fume also show that the long-term shrinkage was not affected significantly. The higher values of shrinkage might be attributed to the duration of curing the mortar specimens. The mortar specimens in this program were cured for initial 7 days only. It has been shown that the ultimate drying shrinkage decreases with increase in the duration of curing the mortars and concretes [5,11,16]. It is clear from this experimental study on the influence of size of fine aggregate on the drying shrinkage that the increase in size of aggregate significantly reduces the long-term drying shrinkage. The proportion of aggregate in concrete has an influence on the drying shrinkage. The study of the aggregate content and water–cement ratio revealed that the effect of water–cement ratio was more pronounced than that of the aggregate content on the drying shrinkage. This is supported by the study [14] on low-, medium- and high-strength concretes. The reduced values of drying shrinkage with the addition of larger size aggregates are due primarily to the restraining action of the aggregate in the mortar.

The long-term drying shrinkage of cementitious products depends directly on the size of the specimens and on their volume–surface ratio. The coarse aggregate and conventional steel bars in concrete restrain the shrinkage in practice [13]. The conventional laboratory models or small specimens overestimate the shrinkage. The shrinkage increases with the age of mortar for all additions of silica fume.

4. Conclusions

The following conclusions were drawn from the experimental results.

(1) The addition of silica fume has a significant influence on the 28 days ultimate drying shrinkage. The ultimate drying shrinkage of mortar increases with increase in the silica fume content. The pozzolanic reaction and pore size refinement mechanisms are responsible mainly for the increased drying shrinkage of mortar at the early ages.

(2) The long-term drying shrinkage of mortar after 365 days was not affected significantly with the addition of silica fume. The rate of increase in the ultimate drying shrinkage of mortar was high up to the age of 365 days. After 365 days, the increase in the ultimate drying shrinkage decreases with the age of mortar.

(3) The ultimate drying shrinkage increases with increase in the silica fume content in series I mortar mixes at the age of 400 and 620 days. The highest drying shrinkage has occurred at 30% silica fume content. At the age of 730 and 1095 days, the highest values of ultimate drying shrinkage were observed at silica fume contents between 17.50% and 20.00%.

(4) In series II mortar mixes, the highest ultimate drying shrinkage values have been observed at 15% silica fume content in all the mortar mixes at all ages except at 28 days. The drying shrinkage of series I mortar mixes was observed to be as high as two times those observed in series II mortar mixes.

(5) The size of aggregate has very significant role on the ultimate drying shrinkage of mortar. The ultimate drying shrinkage of mortar decreases with increase in the size of fine aggregate in the mortars. This reduction in the ultimate drying shrinkage is due to the restraining action of the larger size aggregate.

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