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INFLUENCE OF SUPERPLASTICIZER, PLASTICIZER, AND SILICA FUME ON THE DRYING SHRINKAGE OF HIGH-STRENGTH CONCRETE SUBJECTED TO HOT-DRY FIELD CONDITIONS

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ABSTRACT

The effects of adding condensed silica fume (10% of cement weight) on the concrete mix, and those of adding either superplasticizer or plasticizer on the drying shrinkage (DS) of 12 high-strength concrete prisms exposed to either controlled laboratory or hot-dry field conditions, were monitored for over 3 years. The results indicate that for specimens cured under controlled laboratory conditions, inclusion of silica fume in the concrete mix reduces the 3-year DS by 25%, the induced shrinkage stress by 36% and the first month rate of DS by 21%. The corresponding reduction in the 3-year DS, the induced shrinkage stress, and the first month's rate of DS for the counterpart specimens cured under hot-dry field conditions are 13%, 26%, and 24%, respectively. The results also show that for specimens cured under laboratory conditions, replacing the superplasticizer by plasticizer increases the 3-year DS by 21%, the induced shrinkage stress by 27%, and the first month's rate of DS by 32%. The corresponding increase in the DS, the induced shrinkage stress, and the first month DS for the counterpart specimens cured under the hot-dry field conditions are 27% and 34%, and 35%, respectively. Furthermore, test results indicate that the range of the maximum recorded DS strains in 3-year exposure period is between 450 to 650 μm/m and is dependent on the concrete content of admixtures. On the other hand, depending on the curing conditions, 75 to 80% of the 3-year DS occurs within the first 3 months of exposure. *© 1998 Elsevier Science Ltd*

Introduction

Previous studies carried out on normal-strength concrete (NSC) (1–4) have shown that shrinkage of concrete introduces characteristic problems in reinforced concrete structural members and, if not accurately accounted for at the design stage, can cause severe cracking which, in turn, may lead to service life reduction and impair the structural reliability. Because of that, problems associated with drying shrinkage (DS) of concrete have received more attention by architects, engineers and contractors than any other property of concrete (1).

Over the past years, there has been increased interest in the use of high-strength concrete (HSC). This is particularly the case in high-rise buildings, long-span prestressed concrete bridges, offshore structures, and in similar structures. However, use of HSC demands lower water/cement (w/c) ratio and higher cement content. Although it is well established that when w/c ratio decreases, the amount of drying shrinkage reduces, the rate of shrinkage for HSC is expected to be higher than that of NSC. This may be attributed to the greater cement content of HSC, which is accompanied by a considerably greater amount of heat and thus greater rate of hydration. Furthermore, it becomes common practice to use chemical and mineral admixtures in producing HSC. Unfortunately, there is inconsistent data on their influence on the drying shrinkage of concrete.

Al-Sugair (5) reported the results of shrinkage test on 50 × 50 × 300 prisms made with high-strength concrete and subjected to 30°C and 50% relative humidity (RH) in room A or 55°C and 5% RH in room B. He observed that the DS of HSC specimens, increased as a result of adding silica fume. He added also that the increase was more profound for specimens in room B than those in room A.

Tazawa and Yonekura (6) analyzed the DS of concrete with condensed silica fume and compared the results with those of concrete with no silica fume. Specimens were manufactured under two curing conditions, namely standard and autoclave curing, and their shrinkage strains were measured in air at 20°C and 50% RH. They concluded that, for the same w/c ratio, the DS of specimens containing silica was lower than that of specimens without silica fume. However, in case of standard curing and for concrete with the same compressive strength they observed that the DS per unit cement paste volume were roughly the same for specimens with or without condensed silica fume whereas in the case of autoclave curing the values were higher for concrete with condensed silica fume.

Ravindrajah et al. (7) investigated the effect of curing period and silica fume content on the DS of HSC. They concluded that adding 8% of silica fume increased the 100-day DS of the specimens cured under water for three days by 17%, whereas the DS reduced by 9% when the silica fume increased to 15%. Moreover, they reported that for specimens cured under water for 460 days, inclusion of both 8 and 15% reduced the 100-day DS.

On the other hand, Brooks and Waimwright (8) investigated, for a period of 1 year, the influence of superplasticizer on the DS of 76 × 255 mm HSC cylindrical specimens with different compressive strengths. Half of the specimens were cured under water for 28 days and then stored in air at 22 ± 3 °C and 65 ± 7% RH while the other half of the specimens were kept under water for the whole test period. They reported that the highest shrinkage did not occur in specimens containing the highest quantity of cement, and the shrinkage of the admixture concrete was less than that of its respective control specimens. The researchers also pointed out that such behavior cannot be explained in terms of the quantity of hydrated cement paste alone, but rather speculated that the microcracking played a predominant factor on the test results. They also added that the lower shrinkage of the admixture concrete could be explained in terms of higher volumetric aggregate content compared with those of the control concrete.

Ngab et al. (9) compared the DS of 89 × 89 × 267 mm HSC specimens containing water reducing admixture with that of counterpart normal-strength concrete (NSC) specimens and found that HSC specimens experienced larger shrinkage than the NSC specimens. However, the difference was not significant.

Alexander et al. (10) reported 10 to 25% increase in shrinkage of HSC containing superplasticizer after 20 months of testing.

Brooks (11) investigated the influence of five types of plasticizers and superplasticizers on the drying shrinkage of concrete. He concluded that, due to the addition of superplasticizers and plasticizers, there was a general increase in DS between 3 and 130%, respectively. Also, he observed that some admixtures do not significantly affect shrinkage. However, due the limited published data and the fact that many variables were involved and no significant differences exist between most types of admixtures considered in the study, he did not arrive at some conclusive observations.

Researchers have ascribed the inconsistency of the influence of the silica fume, superplasticizers, and plasticizers on the drying shrinkage of HSC to several reasons, some of which are variations in environmental conditions, curing procedure and period, cement content, superplasticizer and silica fume contents and types, and specimen size. However, to the author's knowledge, when concrete is subjected to hot-dry field conditions, the data available on the influence of adding silica fume and superplasticizer or plasticizer on the drying shrinkage of concrete is almost nil.

It is, therefore, the purpose of this paper to present the results of the study carried out for a period of three years to investigate the effect in adding 10% of silica fume along with either superplasticizer or plasticizer on the drying shrinkage of HSC prisms subjected to either controlled laboratory or uncontrolled hot-dry field conditions.

Experimental Program

Drying shrinkage of 12 prisms of HSC was monitored over a period of 3 years. The prisms were $76 \times 76 \times 286$ mm and the shrinkage strains were measured over an effective gage length of 260 mm. The cement used was of Portland Type I. The sand was of natural desert fine aggregate with a fineness modulus of 3.06, and the coarse aggregate was of locally available crushed limestone with 20 mm maximum size. Both fine and coarse aggregates conformed to the ASTM C33 grading (12).

Three different concrete mixes were used to cast the specimens. All mixes were identical except for the content of the admixtures. The mix proportions (by weight) for water-cement, coarse aggregate-cement, and fine aggregate-cement were 0.3, 1.95, and 1.25. Mix 1 contained a sulphonated naphthalene superplasticizer conforming to ASTM C494 type F at a dosage of 20 ml/kg of cement, had a slump of 175 ± 5 mm, and a 28-day compressive strength (152 mm cubic specimens) of 70.5 MPa. Mix 2 was identical to Mix 1 except that a 10% by weight of cement silicon dioxide silica fume (in addition to the cement weight) was added to the mix; it had a slump of 40 ± 5 mm and a 28-day compressive strength of 92.5 MPa. Mix 3 was identical to Mix 2 except that the superplasticizer was replaced with a polymer-type plasticizer conforming to ASTM Types B and D at a dosage of 30 mL/kg of cement, and had a slump of 40 ± 5 mm and a 28-day compressive strength of 84.8 MPa. Thus, Mixes 2 and 3 had the same slump. Out of each mix, four shrinkage specimens were cast. Further details about the mix proportions and concrete properties are reported in Table 1.

Curing Procedure

All specimens were cast in steel mold, covered with wet burlap, demolded 24 h after casting, and then immersed in tap water at 25 ± 2 °C, prepared in accordance with the ASTM C 192 recommendations for 45 min. Immediately after removing from water, the initial readings were recorded. The specimens were then transferred back to under water and kept there for 7 days. Six of the 12 specimens (two specimens of each mix) were then shifted to the

TABLE 1
Mix proportions, compressive strength (f_c'), and modulus of elasticity (E) for the three mixes.

Mix no.	1	2	3
Type I cement (kg/m^3)	540	540	540
Sand (kg/m^3)	676	676	676
20 mm aggregate (kg/m^3)	1055	1055	1055
Silica fume (kg/m^3)	—	54	54
Superplasticizer (mL/kg of cement)	20	20	—
Plasticizer (mL/kg of cement)	—	—	30
w/c ratio	0.3	0.3	0.3
Slump (mm)	175 ± 5	40 ± 5	40 ± 5
f_c' (MPa) (152 × 305 mm) cylindrical specimens*	56.4	74.0	67.8
E** (GPa)	31.8	35.5	34.2

* f_c' for a 152 × 305 mm cylindrical specimen is 0.8 of f_c' for 152 mm cubic specimen (13).
** Computed using Eq. 5-1 from ref. 14.

controlled laboratory (25 ± 2 °C and 30% RH) environment, covered with burlap and subjected to intermittent water spray twice a day for 21 days and then left to air dry with predefined frequent shrinkage measurements for 3 years. The remaining six specimens, after being kept under water for 7 days, were transferred to the field conditions covered with burlap, subjected to 21 days of intermittent water spraying and then left to air drying with predefined time and interval of shrinkage measurements for 3 years. Some data about the field conditions are reported in the appendix.

Test Results and Discussion

The development of DS with time for all test series considered in this study for a period of 3 years are shown in Figures 1 through 4. Each curve plotted in the figures represents the results of the average shrinkage strains measured for two identical shrinkage specimens dried together under the same curing conditions. The maximum recorded shrinkage strains and the induced stresses due to shrinkage after three years of laboratory and field exposures along with the specimen designations are presented in Table 2. The rate of DS during the first, second, and third months exposure for the three types of specimens when subjected to laboratory and hot-dry field conditions are shown in Figures 5 and 6, respectively. Table 3 reports the ratios of the DS occurred up to the end of the first, second, and third months and also for the first and second years for each type of specimens relative to their respective maximum DS values after 3 years of exposure.

Figures 1 and 2 show that under both the laboratory and field conditions adding 10% of silica fume to the HSC mix reduces the shrinkage strains of concrete with time. As can be seen in Table 2, the average reduction in the maximum measured shrinkage strains of SSL and SSF specimens relative to that of SNSL (specimens containing superplasticizer but no

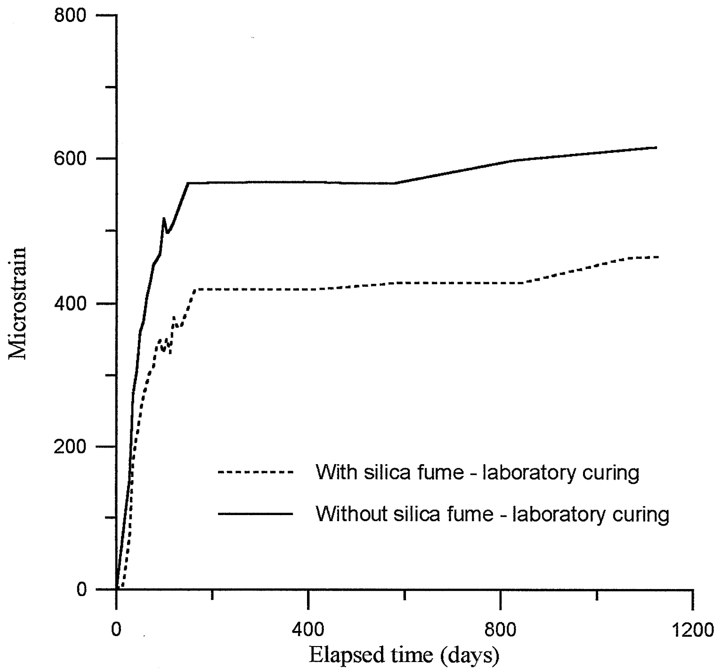

FIG. 1.
Effect of silica fume on the drying shrinkage of concrete subjected to controlled laboratory conditions.

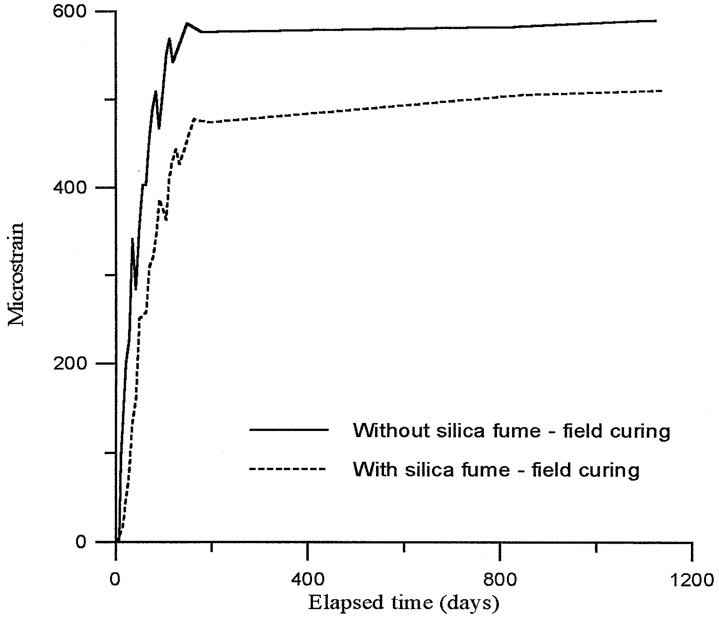

FIG. 2.
Effect of silica fume on the drying shrinkage of concrete subjected to hot-dry field conditions.

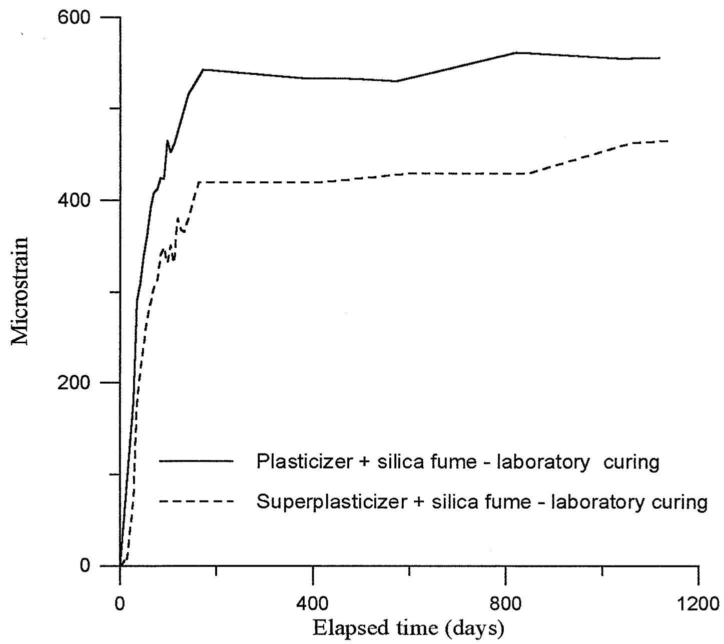

FIG. 3.

Effect of replacing superplasticizer with plasticizer on the drying shrinkage of concrete subjected to controlled laboratory conditions.

silica fume and subjected to controlled laboratory curing conditions) and SNSF (specimens containing superplasticizer but no silica fume and subjected to hot-dry field curing conditions) specimens are 25 and 13%, respectively. The reduction in the shrinkage of the SSL (specimens containing superplasticizer and silica fume and subjected to controlled laboratory curing conditions) and SSF (specimens containing superplasticizer and silica fume and subjected to hot-dry field curing conditions) specimens may be ascribed to the well-known influence of silica fume in reducing the small capillary pores of the mature concrete which, in turn, reduces the diffusion of the capillary and adsorbed water to the environment—the main cause of the drying shrinkage mechanism. The results reported in Table 2 also reveal that the reduction in the DS of concrete due to the addition of the silica fume reduced the DS induced stresses of SSL and SSF specimens relative to that of their respective SNSL and SNSF specimens by 36 and 26%, respectively.

On the other hand, the results presented in Figures 3 and 4 and Table 2 indicate that replacing the superplasticizer with the plasticizer increases the DS of PSL (specimens containing plasticizer and silica fume and subjected to controlled laboratory curing conditions) and PSF (specimens containing plasticizer and silica fume and subjected to hot-dry field curing conditions) specimens relative to that of SSL and SSF by 21 and 27%, respectively. This may be attributed to the fact that plasticizer is less efficient in dispersing the cement paste particles in water than superplasticizer, and therefore concrete containing plasticizer has lower rate of hydration and building up strength and, in turn, less resistance

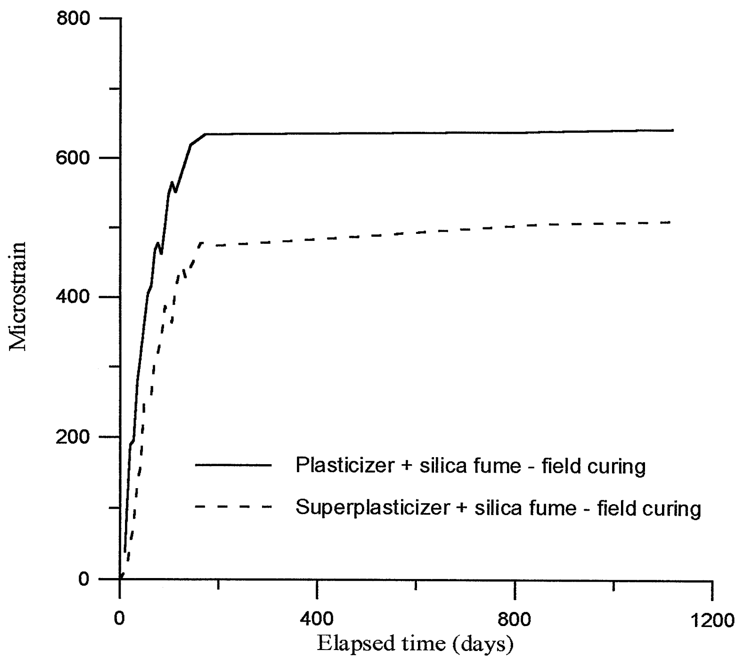

FIG. 4.
Effect of replacing superplasticizer with plasticizer on the drying shrinkage of concrete subjected to hot-dry field conditions.

TABLE 2
Analysis of shrinkage strains after three years of exposure to laboratory and field conditions.

	Laboratory environment			Field environment		
Specimen designation	SNSL	SSL	PSL	SNSF	SSF	PSF
MRSS $\times$ 10^6*	616	465	562	590	511	643
Effect of silica fume, %	0	−25	—	0	−13	—
Effect of replacing superplasticizer with plasticizer, %	—	0	21	—	0	27
σ_{MRSS} (MPa)**	19.6	16.5	19.3	18.5	17.9	21.9
σ_{MRSS}/f_c' (%)	34.7	22.3	28.3	32.8	24.2	32.3
Effect of silica fume, %	0	−36	—	0	−26	—
Effect of replacing superplasticizer with plasticizer, %	—	0	27	—	0	34

* MRSS, maximum recorded shrinkage strain.
** $\sigma_{MRSS} = E \times$ MRSS.

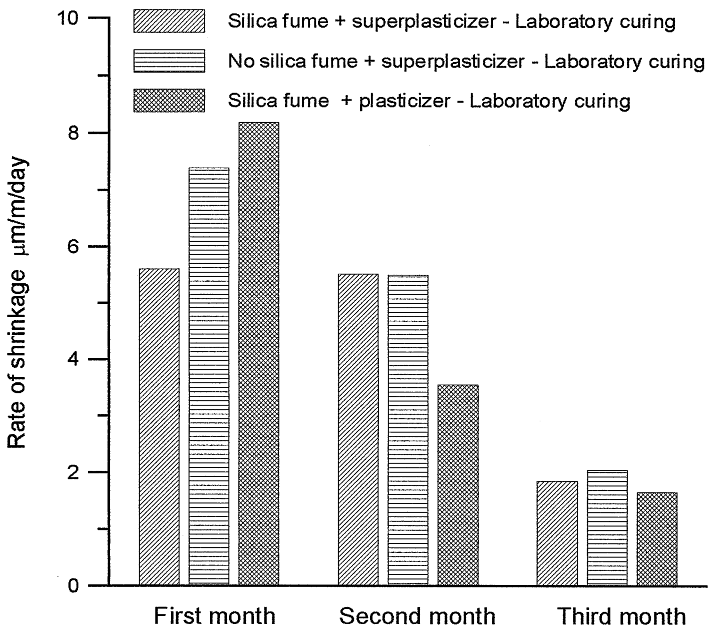

FIG. 5.
Comparison between the rate of DS during the first, second, and third months of exposure for the three types of concrete mixes (controlled laboratory curing conditions).

to DS than concrete containing superplasticizer. Thus, the plasticizer specimens experienced higher DS than their counterpart superplasticizer specimens. Furthermore, the results in the same table indicate that the increase in the DS due to the replacement of superplasticizer by the plasticizer increased the induced DS stresses of the PSL and PSF specimens relative to that of their respective SSL and SSF specimens by 27 and 34%, respectively.

The results shown in Figures 5 and 6 show that the combined effect of silica fume and superplasticizer reduced the rate of the first month DS of SSL specimens, where concrete is not fully hardened, relative to that of SNSL specimens by 21% and to that of PSL by 32%. Similarly, the first month's rate of DS of SSF specimens is 24% lower than that of SNSF specimens, and 35% lower than that of PSF specimens. Moreover, the difference between the first month rate of DS of SSL and SSF specimens due to the change of the curing conditions, laboratory versus field conditions, is less than 10% whereas the difference between the DS of SNSL and SNSF specimens is 22%. This clearly shows that silica fume addition helps in reducing the sensitivity of concrete to the curing conditions. This was also confirmed by the previous finding of Alsayed (13). Because the capillary and adsorbed water is reduced after 1 month of expsosure, the rates of the DS for the three types of specimens during the second and third months of laboratory and field exposures as shown in Figures 5 and 6 are lower than that of their respective specimens during the first month of exposure.

It is worth observing in Figure 6 that during the second and third months of exposure the rate of DS of SSF specimens is higher than that for SNSF specimens. This may be attributed to the silica fume influence in densifying the hydrated cementitious paste (pozzolanic effect)

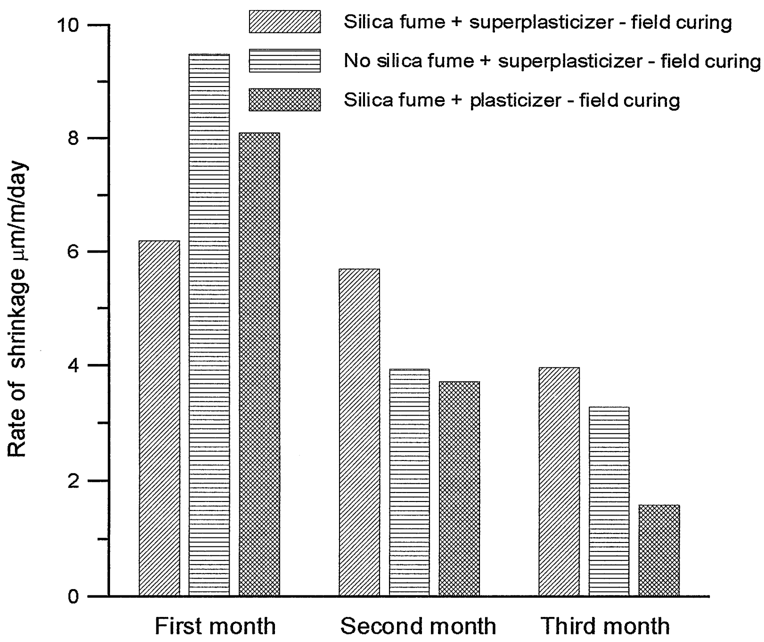

FIG. 6.

Comparison between the rate of DS during the first, second, and third months of exposure for three types of concrete mixes (hot-dry field curing conditions).

(15,16), which takes place mostly between the ages of 3 and 28 days (17). This pozzolanic effect of silica fume reduces the concrete permeability and, in turn, slows down the rate of DS of SSF specimens. Therefore, the difference between the first and second month's rate of DS for SSF specimens becomes lower than that of the respective SNSF specimens. However, such differences in the rate of DS for SSF and SNSF specimens have limited practical effect,

TABLE 3

Relationship between percentage of DS and period of exposure relative to the 3-year DS.

	Laboratory environment			Field environment		
Period	SNSL	SSL	PSL	SNSF	SSF	PSF
1 month	33	22	40	45	36	36
2 months	65	60	67	69	51	64
3 months	76	75	75	80	77	79
1 year	92	90	93	98	97	85
2 years	92	96	99	99	98	99
3 years	100	100	100	100	100	100

as after the first month of exposure concrete has already built up most of its rigidity and strength, which enhances its resistance to shrinkage deformation.

It is also worth mentioning here that depending on the ingredient of the concrete mix considered in this study, the total amount of DS after 3 years of exposure ranges between 450 to 650 μm/m, that is, about 0.4 to 0.6 μm/m/day. The maximum recorded shrinkage strains for specimens cured under laboratory conditions are in agreement with the results obtained by other researchers (9,18) and are within the same range usually reported for normal strength concrete (19).

The results reported in Table 3 show that the influence of mineral and chemical admixture considered in this study is more pronounced at the first and second months of exposure and declines afterwards. The results reported in Table 3 also clarify that about 75% of the DS of the laboratory cured specimens and 80% of that of the field cured specimens occurred by the end of the third month of exposure, which is about the same ratio reported for normal strength concrete (19). However, less than 10% of the 3-year DS occurred in the third year.

Conclusions

Based on the results obtained by monitoring the drying shrinkage (DS) of 12 concrete prisms subjected for three years to controlled laboratory or hot-dry field conditions, the following conclusions may be drawn:

1. Adding silica fume (10% of cement weight) to concrete mix greatly reduces the 3-year DS, the stress due to shrinkage strain, and the rate of first month DS of concrete. This is true whether concrete is subjected to controlled laboratory or hot-dry field curing conditions.
2. Replacing superplasticizer with plasticizer increases the 3-year DS, the stress due to shrinkage strain, and the rate of the first month DS of concrete. This is true whether concrete is cured under controlled laboratory or hot-dry field conditions.
3 Adding mineral and/or chemical admixtures to concrete mix has an appreciable influence on the total amount of DS. Depending on the content of the admixture, the maximum DS strains in 3 years of exposure ranges between 450 to 650 μm/m, i.e., 0.4 to 0.6 μm/m/day
4 Adding 10% of cement weight as silica fume to concrete mix greatly reduces the influence of curing conditions on the rate of DS.
5 Depending on the curing conditions, 75 to 80% of the 3-year DS occurs during the first 3 months of exposure and less than 10% of that 3-year DS occurs during the third year.

References

1. ACI Committee 224, Control of Cracking in Concrete Structures, (ACI 224R-90), ACI, Detroit, 1990.
2. V. Novokshchenov, Concr. Int. 4, 27 (1986).
3. S.K. Oha, Concr. Int. 8, 24 (1986).
4. H. Imai, K. Okada, T. Kojima, and Y. Mizumoto, Proceedings, Japan Society of Civil Engineering, Tokyo, No. 340, 315, 1983.
5. F.H. Al-Sugair, Mag. Concr. Res. 47, 77 (1995).
6. E. Tazawa and A. Yonekura, Proc. of the 2nd CANMET/ACI Int. Conf.: Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Madrid, Spain, (ACI SP-91), p. 21, April, 1986.

7. R.S. Ravindrarajah, C.M. Mercer, and J. Toth, Proceedings ACI International Conference on High Performance Concrete (ACI SP-149), Singapore, p. 475, 1994.
8. J.J. Brooks and P.J. Wainwright, Mag. Concr. Res., 25, 205 (1983).
9. A.S. Ngab, A.H. Nilson, and F.O. Slate, ACI J. 78, 225 (1981).
10. K.M. Alexander, G.M. Bruere, and I. Ivanusec, Cem. Concr. Res. 10, 131 (1980).
11. J.J. Brooks, Mag. Conc. Res. 41, 145 (1989).
12. American Society for Testing Materials Standard, Section 4 -Construction, ASTM, Philadelphia, PA, 1992.
13. S.H. Alsayed, ACI Mat. J., 94, 6, (1997).
14. ACI Committee 363, "State of the Art Report on High- Strength Concrete," (ACI 363R-84), ACI, Detroit, 1984.
15. M. Regourd, B. Mortureux, P.C. Aitein, and P. Pinsonneault, Fourth Int. Conf. on Cement Microscopy, Las Vegas, 3, March, 1983.
16. P.C. Aitein, S.L. Sarkar, and P. Laplante, Concr. Int. 12, 40 (1990).
17. E.J. Sellevold, and F.F. Radjy, Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete, SP-79, ACI, Detroit, 677 (1983).
18. Y. Seng, and B.V. Rangan, ACI Mat. J. 87, 440 (1990).
19. A.M. Neville, Properties of Concrete, 3rd Edition, p. 779, London, Pitman Pub., 1981.

Appendix

Average Riyadh monthly dry bulb temperature (DBT) and relative humidity (RH) during the period of DS measurements.

Month	DBT Min (°C)	DBT Max (°C)	RH Mean (%)
Jan.	8.79	19.58	57.22
Feb.	11.40	22.04	46.74
March	13.86	24.49	47.23
Apr.	18.28	29.93	39.28
May	23.98	37.53	17.21
June	26.35	40.30	11.30
July	28.09	41.28	11.21
Aug.	27.52	41.93	11.50
Sep.	23.28	38.04	14.79
Oct.	19.44	33.65	20.98
Nov.	13.17	25.37	35.41
Dec.	10.21	19.80	62.05