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Effect of silica fume on mechanical properties of high-strength concrete

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Abstract

This paper presents the results of experimental work on short- and long-term mechanical properties of high-strength concrete containing different levels of silica fume. The aim of the study was to investigate the effects of binder systems containing different levels of silica fume on fresh and mechanical properties of concrete. The work focused on concrete mixes having a fixed water/binder ratio of 0.35 and a constant total binder content of 500 kg/m^3. The percentages of silica fume that replaced cement in this research were: 0%, 6%, 10% and 15%. Apart from measuring the workability of fresh concrete, the mechanical properties evaluated were: development of compressive strength; secant modulus of elasticity; strain due to creep, shrinkage, swelling and moisture movement. The results of this research indicate that as the proportion of silica fume increased, the workability of concrete decreased but its short-term mechanical properties such as 28-day compressive strength and secant modulus improved. Also the percentages of silica fume replacement did not have a significant influence on total shrinkage; however, the autogenous shrinkage of concrete increased as the amount of silica fume increased. Moreover, the basic creep of concrete decreased at higher silica fume replacement levels. Drying creep (total creep – basic creep) of specimens was negligible in this investigation. The results of swelling tests after shrinkage and creep indicate that increasing the proportion of silica fume lowered the amount of expansion. Because the existing models for predicting creep and shrinkage were inaccurate for high-strength concrete containing silica fume, alternative prediction models are presented here.

Keywords: High-strength concrete; Silica fume; Compressive strength; Elastic modulus; Creep; Shrinkage; Swelling

1. Introduction

Nowadays high-strength and high-performance concrete are widely used throughout the world and to produce them it is necessary to reduce the water/binder ratio and increase the binder content. Superplasticisers are used in these concretes to achieve the required workability; moreover, different kinds of cement replacement materials are usually added to them because a low porosity and permeability are desirable. Silica fume is the one of the most popular pozzolanas, whose addition to concrete mixtures results in lower porosity, permeability and bleeding because their oxides (SiO_2) react with and consume calcium hydroxides, which are produced by the hydration of ordinary Portland cement. The main results of pozzolanic reactions are: lower heat liberation and strength development; lime-consuming activity; smaller pore size distribution.

In high-performance concrete, which contains high quality and expensive materials, cracking provides the greatest concerns for the designers because harmful materials can penetrate from them to the concrete easily and start to destroy it and also corrode reinforcement. Some of these cracks are related to drying and autogenous shrinkage of concrete. Therefore, to improve the durability of high-strength concrete, its autogenous and drying shrinkage should be addressed and necessary work on its mix design should be done to minimize them. It is worth noting that autogenous shrinkage of concrete is because of chemical reactions during the hydration of cementitious materials; nevertheless, drying shrinkage occurs as a result of moisture movement from concrete to the atmosphere.

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High-performance concrete should be controlled during its early ages. For instance, fresh concrete may bleed or coarse aggregates may separate from the paste. Also its volume changes at this age are very important. Of course before initial set, concrete has plastic properties and has high-tension strain capacity; consequently, the possibility of cracking in it is low. However, shrinkage at this age may weaken the transition zone between aggregates and paste, thus drying shrinkage cracking may increase in future [1]. Another point is initial set and the creation of the internal skeleton of concrete. At this age tension strain capacity of concrete is too low and therefore it is very sensitive to shrinkage cracks [2]. Moreover, Holt [1] shows the maximum autogenous shrinkage often occurs at this age.

Current methods of estimating movements in concrete, such as ACI [3] and CEB [4], do not apply for high-performance concrete. They were developed for plain concrete before the extensive use of mineral and chemical admixtures. In addition, shrinkage of high-performance concrete has a significant contribution from autogenous shrinkage and less contribution from drying shrinkage; only the latter is considered by prediction methods. In order to develop existing or new prediction models, experimental data are needed.

This paper compares strength, elasticity, shrinkage, swelling, creep and moisture movement of high-strength concretes containing different levels of silica fume.

2. Materials and mix proportions

The cementitious materials used were ordinary Portland cement (OPC) and silica fume (SF), their chemical compositions and physical properties being given in Table 1. Details of the mix proportions for the concrete containing different levels of silica fume are given in Table 2. Crushed granite sand and gravel with a nominal maximum size of 10 mm were used as the aggregates. The control mix was cast using OPC, while the other mixes were prepared by replacing part of the cement with silica fume at four different replacement levels on mass-for-mass basis. The water/cement ratio and the slump of control high-strength concrete were 0.35 and 100 ± 10 mm, respectively. The same water/binder ratio of 0.35 was used for the other concrete mixes with the same amount of slump. Consequently, the dosage of superplasticiser changed due to the effect of the different levels of silica fume. The superplasticiser used is based on melamine formaldehyde and lignosulfonate.

Table 1
Chemical composition and physical properties of cementitious materials

Item	Cementitious materials, %	
	Ordinary Portland cement	Silica fume
SiO_2	21.46	91.70
Al_2O_3	5.55	1
Fe_2O_3	3.46	0.9
CaO	63.95	1.68
MgO	1.86	1.8
Cl	–	0.08
SO_3	1.42	0.87
K_2O	0.54	–
Na_2O	0.26	–
LOI	–	2
	Compounds	
C_3S	50.96	–
C_2S	23.1	–
C_3A	8.85	–
C_4AF	10.53	–
	Fineness	
SSA (m^2/kg)	330	14,000

Table 2
Mix proportions of concrete containing different levels of silica fume

Mix components	Concrete mixes			
	OPC	SF6	SF10	SF15
Cement (kg/m^3)	500	470	450	425
Silica fume (kg/m^3)	–	30	50	75
Superplasticiser (kg/m^3)	8.17	9.78	11.71	13.34

Gravel: 1203 kg/m^3, sand: 647 kg/m^3, water: 175 kg/m^3, $W/b = 0.35$.

3. Test procedure

For each mix, the following specimens were made: 24 100 mm cubes for compressive strength; eight 80×270 (diameter $\times$ length) mm cylinders for creep; four 80×270 mm and four 150×300 mm cylinders for shrinkage; two 80×270 mm and two 150×300 mm cylinders for swelling. After being de-moulded at the age of one day, all creep and shrinkage specimens were cured in water at 20 ± 2 °C until the age of 7 days. Subsequently, half of them were sealed and then all creep and shrinkage specimens were kept in a controlled environment of 20 ± 2 °C and 50 ± 5% relative humidity throughout the test duration. Compressive strength and swelling specimens remained in 20 ± 2 °C water all the time.

The specimens of autogenous shrinkage and basic creep were sealed with aluminium waterproofing tape, which was found to be very effective since the specimens showed very minimal weight loss. The OPC control mix recorded a weight loss of 0.03% after 240 days. This is well within the limit of 0.05% as recommended by the JCI [5]. The measurement of shrinkage and creep was performed using a mechanical Demec gauge of 100 mm gauge length at four circumferential positions of the specimens. This measurement commenced at about 7 days after casting, i.e. after specimens were removed from the water tank. The measurement of swelling started at about 24 h after casting, i.e. after specimens were de-moulded and stored in water.

Compressive strength was determined according to BS 1881: Part 116: 1983 at various ages over a period of 400 days. The apparatus and method of strain measurement used for shrinkage, swelling and creep were those as described previously [6]. For the determination of total and basic creep, total and autogenous shrinkage were treated as being additive respectively, i.e. creep is defined as the change in deformation since application of load, corrected for shrinkage of companion load-free specimen. At the ages of 7 and 28 days, creep specimens were subjected to a sustained compressive stress of 10 MPa, which corresponded to a range of initial stress/strength ratio of 0.14 to 0.22, until the age of $\approx$400 days.

4. Results and discussion

4.1. Workability of fresh concrete

Table 2 shows the dosage of superplasticiser which was necessary for mixes containing different levels of silica fume to have a constant slump of 100 ± 10 mm, measured according to BS 1881: Part 102: 1983. It can be observed that the mixes incorporating higher silica fume content tended to require higher dosages of superplasticiser. The higher demand of superplasticiser with the concrete containing silica fume can be attributed to the very fine particle size of silica fume that causes some of the superplasticiser being adsorbed on its surface [7]. It is worth adding that mixes incorporating more silica fume were more cohesive and this is in agreement with the findings of Khatri and Sirivivatnanon [7].

4.2. Compressive strength

For concrete stored in water, the development of compressive strength with age is shown in Table 3. It can be seen that the compressive strength development of concrete mixtures containing silica fume was negligible after the age of 90 days; however, there were 26% and 14% strength increases in the control concrete after one year compared to its 28 and 90 days strength, respectively. The difference in strength development in OPC concrete and SF concrete can be attributed [8] to the rapid formation of an inhibiting layer of reaction product preventing further reaction of SF with calcium hydroxide beyond 90 days. In the case of the control concrete, hydration is at a less advanced stage and strength still shows significant increases. According to Neville and Brooks [9] the 365-day/28-day strength ratio is about 1.25 in concrete without mineral admixtures, which is quite near the results of this experiment. At the age of 400 days, the compressive strength of control concrete and concrete mixes containing different proportions of silica fume were the same. However, at the age of 28 days, the strength of concrete containing 15% silica fume was about 21% more than that of control concrete. Therefore, the inclusion of silica fume in concrete mixture, mainly affects short-term strength of concrete. It is of interest to compare the strength of dry-stored concrete with that of the wet-stored. The casting programme included three specimens of each mix that were cured in water for 7 days and then kept in the control room of 20 ± 2 °C and 50 ± 5% relative humidity until the age of 400 days. The results of their 400-day compressive strength and moist cured specimens for 400 days are compared in Table 4. It can be seen that moist curing has improved the compressive strength of control concrete about 10% but it did not have any significant effects on specimens containing silica fume. It is worth adding that utilizing silica fume contributed to the compressive strength of dry-stored specimens by about 9% at the age of 400 days. However, it had no influence on long-term strength of wet-stored concrete. According to the Concrete Society [10] concrete containing silica fume should be moist cured at least for 7 days.

Table 3
Development of compressive strength with age (MPa)

Concrete mixes	Age (days)						
	7	14	28	42	90	365	400
OPC	46	52	58	62	64	73	74
SF6	50.5	58	65	69	71	73	73
SF10	52	61	67.5	71	74	74	73
SF15	53	63	70	73	76	75	76

4.3. Elastic modulus

The results of secant modulus of elasticity of concrete specimens containing different levels of silica fume, which were obtained in the creep tests, are shown in Table 5. In fact, the cylindrical specimens of 80×270 mm height were loaded at the ages of 7 and 28 days. Because secant modulus is related to the level of applied stress and also loading rate, all the specimens of this research were subjected to a stress of 10 MPa and the time taken to apply it was about 10 min; the stress/strength ratio was between 0.14 and 0.22. As shown in Table 5, increasing the silica fume replacement level increases the secant modulus of concrete. Also ACI 318-95 [11] has predicted the static modulus of the investigated

Table 4
Compressive strength of dry and moist cured specimens after 400 days (MPa)

Method of curing	Concrete mixes			
	OPC	SF6	SF10	SF15
Moist	74	73	73	76
Dry	67	72	73	74

Table 5
7- and 28-day compressive strength and secant modulus of elasticity

Kind and age of concrete		Compressive strength (MPa)	Measured modulus (GPa)	Predicted modulus by Eq. (1) (GPa)
OPC	7 days	46	28.8	30.2
	28 days	58	34.4	34
SF6	7 days	50.5	31	31.7
	28 days	65	35.5	36
SF10	7 days	52	31.1	32.2
	28 days	67.5	37	36.6
SF15	7 days	53	31.5	32.5
	28 days	70	38.1	37.3

Table 6
400-day compressive strength and elastic modulus recovery

Kind of concrete and age of loading		Measured modulus (GPa)	Compressive strength (MPa)	Predicted modulus by Eq. (1) (GPa)
OPC	7 days	38	74	38.4
	28 days	38.12		
SF6	7 days	38.23	73	38.1
	28 days	38.1		
SF10	7 days	38.21	73	38.1
	28 days	38.3		
SF15	7 days	38.64	76	38.9
	28 days	38.75		

specimens properly. This is in agreement with the previous findings [12]. It is worth noting that sealed and drying specimens had similar values of secant modulus. ACI 318-95 [11] presents the following equation to calculate elastic modulus:

$$E_c = 4.7(f_c)^{0.5} \tag{1}$$

where f_c is the compressive strength of standard cylinder specimen of 150×300 mm height in MPa and E_c is static modulus in GPa.

Because 100 mm cube specimens were utilized to measure the compressive strength, a factor of 0.9 has been used to estimate the equivalent cylinder strength. This factor is greater than the usual factor of 0.8 that is generally used for lower strength concrete, and was chosen after considering recent data presented by Imam et al. [13].

Elastic modulus recovery was calculated by dividing the sustained 10 MPa stress to instantaneous strain recovery at the time of unloading. It should be mentioned that the specimens loaded at the ages of 7 and 28 days, remained under the load for 396 and 376 days, respectively, so that they were unloaded at the ages of 403 and 404 days, respectively. The compressive strength of concrete at these ages was assumed to be equal to their 400-day strength. Table 6 shows the measured elastic modulus recovery, compressive strength and estimated elastic modulus recovery according to the ACI 318-95 [11]. As shown in this table, loading age and silica fume replacement level had no influence on the elastic modulus recovery. Also the ACI 318-95 [11] (Eq. (1)) could predict this modulus with acceptable accuracy.

4.4. Swelling

Table 7 shows the swelling characteristics for the various types of concrete with different proportions of silica fume. These results are related to the cylindrical specimens of 80×270 mm and 150×300 mm height. It is worth noting that the latter specimens exhibit very little decrease in swelling. This could be explained simply in terms of the larger diameter of the 150×300 mm height specimens, which cause more difficulties for water to penetrate their internal layers and also self-desication. Increasing the silica fume replacement level decreased the swelling of concrete at all ages. Rao [14] and also Fattuhi and Al-Khaiat [15] agree with this finding. It has also been reported that increasing the level of silica fume lowers the permeability of concrete [16] and, consequently, the penetration of water decreases.

4.5. Shrinkage

Figs. 1 and 2 show the shrinkage of cylindrical specimens of 80×270 mm and 150×300 mm height, respectively. Also shown are the predictions by the ACI 209 [3] and the CEB-FIP 1990 [4] methods, which were developed for drying shrinkage only, i.e. they do not really apply to autogenous (sealed) shrinkage. Figs. 1 and 2 show that at early ages both methods tend to underestimate the shrinkage of drying specimens but, at

Table 7
Swelling of 80×270 mm and 150×300 mm high specimens in microstrain

Age (days)	Concrete mixes							
	OPC		SF6		SF10		SF15	
	80 × 270 mm	150 × 300 mm	80 × 270 mm	150 × 300 mm	80 × 270 mm	150 × 300 mm	80 × 270 mm	150 × 300 mm
25	128	124	112	106	96	93	64	61
100	144	140	112	108	128	124	80	78
425	168	165	152	148	152	150	128	125

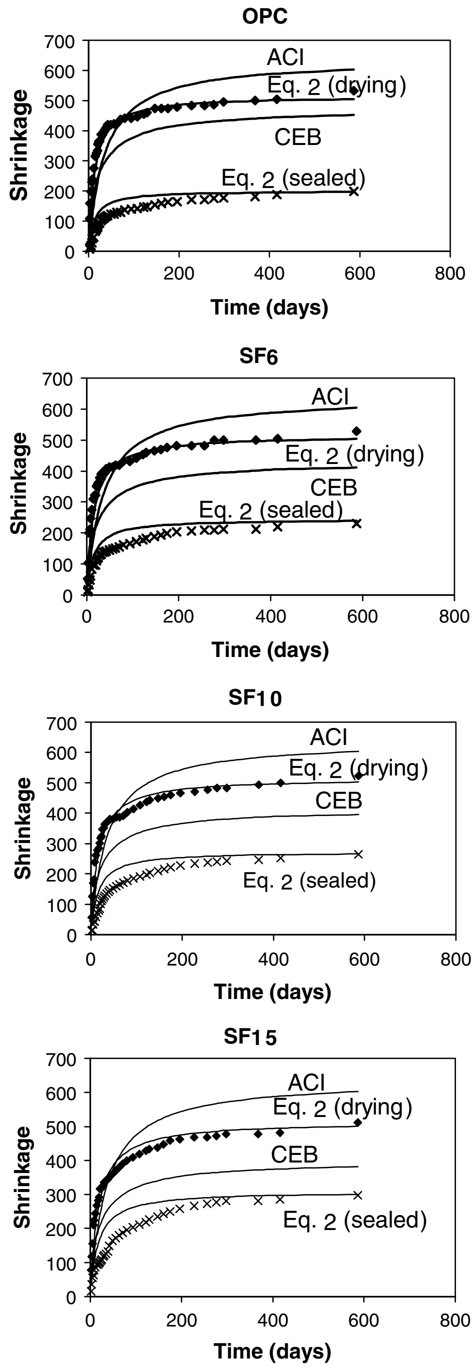

Fig. 1. Shrinkage of 80×270 mm high specimens (microstrain).

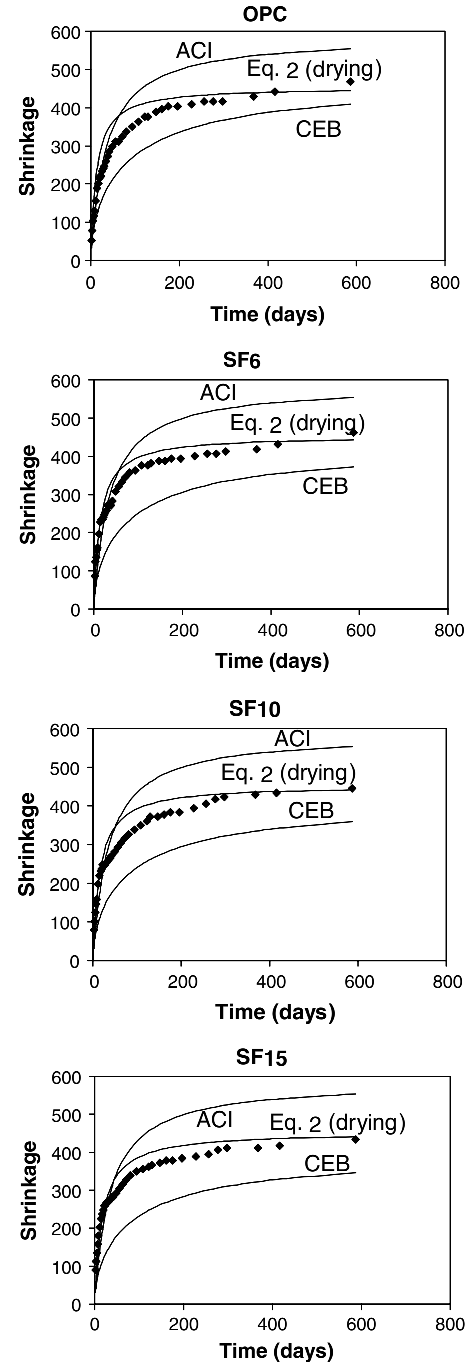

Fig. 2. Shrinkage of 150×300 mm high specimens (microstrain).

later ages, the CEB and ACI underestimate and overestimate total shrinkage, respectively. For the shrinkage determined in this investigation the following expression was developed using regression analysis:

$$\varepsilon_{\mathrm{sh}}(t) = \frac{(t)}{(0.3\mathrm{SF} + 12.6) + (t)} * 516 * y * 10^{-6} \qquad (2)$$

where $y = y_{\mathrm{d}} = 1.14 - 0.007(V/S) \geqslant y_{\mathrm{s}}$ (for drying specimens), or $y = y_{\mathrm{s}} = 0.014\mathrm{SF} + 0.39$ (for sealed specimens), V/S = volume to surface ratio, SF = silica fume percentage, $\varepsilon_{\mathrm{sh}}(t)$ = shrinkage after t days of drying.

Figs. 1 and 2 demonstrate the improvements in predictions using Eq. (2) compared with those by the ACI and CEB methods. Tables 8 and 9 compare the final measured shrinkage of 80×270 mm and 150×300 mm high specimens with the results of different prediction methods. According to Neville et al. [17] the error coefficients of the above-mentioned models can be compared by the following equation:

Table 8
Shrinkage of 80 × 270 mm high specimens after 587 days of drying (microstrain)

Concrete mixes	Measured value	Predicted value		
		Eq. (2)	ACI [3]	CEB [4]
OPC	532	505	604	452
SF6	528	504	604	412
SF10	523	503	604	397
SF15	512	501	604	382
Error coefficient (%)		4.0	15.4	22.5

Table 9
Shrinkage of 150 × 300 mm high specimens after 406 days of drying (microstrain)

Concrete mixes	Measured value	Predicted value		
		Eq. (2)	ACI [3]	CEB [4]
OPC	468	445	554	409
SF6	462	443	554	373
SF10	446	442	554	359
SF15	435	441	554	346
Error coefficient (%)		3.1	23.3	18.2

$$M = \frac{1}{\mathrm{Cav}(t)} \sum \left[\frac{[\mathrm{Cm}(t) - \mathrm{Cp}(t)]^2}{n} \right]^{0.5} * 100 \qquad (3)$$

where M = error coeficient, $\mathrm{Cm}(t)$ = observed shrinkage or creep after time t, $\mathrm{Cp}(t)$ = predicted shrinkage or creep after time t, $\mathrm{Cav}(t)$ = mean observed shrinkage or creep for a number of observations n.

As shown in these tables, the error coefficients of Eq. (2) are much less than those of the ACI and CEB prediction methods. The ACI and CEB prediction equations are:

$$\varepsilon_{sh}(t) = t/(35 + t) \ * \ \varepsilon_{sh}(u) \quad \text{(ACI209-92)}$$

where $\varepsilon_{sh}(u)$ = ultimate shrinkage and

$$\varepsilon_{sh}(t) = [t/(\beta_{sh} + t)]^{0.5} \ * \ \varepsilon_{sh}(u) \quad \text{(CEB-FIP1990)}$$

where β_{sh} = shape function of the specimen.

Also Figs. 1 and 2 show that silica fume did not have considerable influence on drying specimens (total shrinkage). The average amount of total shrinkage after 587 days of drying for the 80 × 270 mm and 150 × 300 mm specimens was 524 and 450 microstrain, respectively, with corresponding standard deviations of 7.5 and 14.2, respectively. It should be noted that Bissonnette et al. [18] disagree with this finding and believe the ultimate deformation does not differ much from one specimen size to the other and only the rate of drying is affected by the size of the specimen. Figs. 1 and 2 also show silica fume to considerably affect the shrinkage of sealed specimens. It is clear that the general effect of increasing the silica fume inclusion is to increase autogenous shrinkage. This is in agreement with the results of other researchers [19–23].

Table 10
Values of total, autogenous and drying shrinkage of 80 × 270 mm high specimens on completion of the tests (microstrain)

Kind of shrinkage	Concrete mixes			
	OPC	SF6	SF10	SF15
Total	532	528	523	512
Autogenous	198	231	264	297
Drying	334	297	259	215

Generally, the levels of shrinkage of drying concrete seemed quite large for a water/binder ratio of 0.35. This fearure can be attributed to a lower volume of aggregate in the high-strength concrete, which acts as a restraint to shrinkage of the cement paste.

Table 10 shows total shrinkage, autogenous shrinkage and also the difference between them, which is drying shrinkage, for the 80 × 270 mm high specimens after 587 days of drying. As it can be seen, there is significant increase in autogenous shrinkage at high levels of silica fume. In fact, inclusion of 10% and 15% silica fume increases the autogenous shrinkage of concrete by 33% and 50%, respectively. The effect of silica fume on autogenous shrinkage can be explained by its influence on the pore structure and pore size distribution of concrete as well as its pozzolanic reaction. According to Sellevold [24] the inclusion of silica fume at high replacement levels significantly increases the autogenous shrinkage of concrete due to the refinement of pore size distribution that leads to a further increase in capillary tension and more contraction of the cement paste. Previous experimental results [25] on the pore structure of mortars using mercury porosimetry technique showed that as silica fume content increased, the pore size distribution was shifted toward a finer distribution, the average pore size reduced and the porosity decreased. It was found that the addition of silica fume and also the dosage of silica fume greatly influence the self-desiccation and autogenous shrinkage of cement paste. In addition, the pozzolanic reaction of silica fume, which was found to be less sensitive to self-desiccation, also leads to an increase in autogenous shrinkage [26].

The high level of autogenous shrinkage of the high-strengh concrete mixes reported here has practical implications. Autogenous shrinkage of concrete occurs as a result of chemical reactions during the hydration of cementitious materials and is not related to moisture movement from concrete to the atmosphere. This means large sizes of structural elements or painting the surface of them do not reduce this kind of shrinkage. Consequently, any restraint to the deformation can induce tension stress and cracking in concrete members. For instance, the reinforcement bars of structural elements [27] or stiff structural supports or even adjacent structural members can resist autogenous shrinkage and cause microcracks. Cracking can increase the permeability of concrete and therefore, especially in severe environments, its durability decreases [28]. It should be mentioned that Loukili et al. [29] believe this shrinkage in very high-strength concrete stops after 10 days.

This investigation shows one of the ways to minimize autogenous shrinkage and also the cracking probability of high-strength concrete is to add not more than 10% silica fume to the mix. Some other researches believe that fiber reinforced concrete is very useful in this field [30–34]. Of course, new recommendations of RILEM [35] should be considered in steel fibers. Some investigators recommend utilizing expansive admixtures to compensate autogenous shrinkage [36,37]. Another method is to use lightweight aggregates in concrete [38] because their water adsorption is high and the internal water lost by self-desiccation of cement paste is immediately replaced by moisture from the lightweight aggregate. Also shrinkage-reducing admixtures are useful to decrease autogenous shrinkage [39]. These chemical materials reduce the surface tension of capillary water. Montani [40] has suggested applying expansive and shrinkage-reducing admixtures together as a method to control concrete shrinkage.

4.6. Creep

Figs. 3 and 4 show the results of specific creep, i.e. creep per unit stress, for cylindrical specimens of 80×270 mm height, which were loaded at the ages of 7 and 28 days, respectively. Specimens were subjected to a sustained compressive stress of 10 MPa during all the creep tests and the stress/strength ratios were less than 0.3. The basic creep of sealed specimens can be compared to the total creep of drying specimens. It can be observed that the difference in creep of unsealed and sealed specimens is small in the control concrete and almost zero in specimens containing silica fume. This implies that there is no interaction between creep and shrinkage and also factors affecting the rate of drying, which are specimen size and the relative humidity of atmosphere, had no influence on the creep of the high-strength concrete specimens investigated here.

The predictions by the ACI [3] and CEB [4] methods are compared to the results of this investigation in Figs. 3 and 4, which in fact show that both methods overestimate the creep. Consequently, for this investigation, a satisfactory model is expressed using regression analysis as follows:

$$C(t) = \frac{(t)^{0.6}}{(26.5 - \mathrm{SF}) + (t)^{0.6}} \times (103 - 3.65\mathrm{SF}) \times y \times 10^{-6} \tag{4}$$

where $y = 1.08 - 0.0114t_0$ (correction factor according to the loading age t_0), SF = silica fume percentage, $C(t)$ = specific creep after t days of loading.

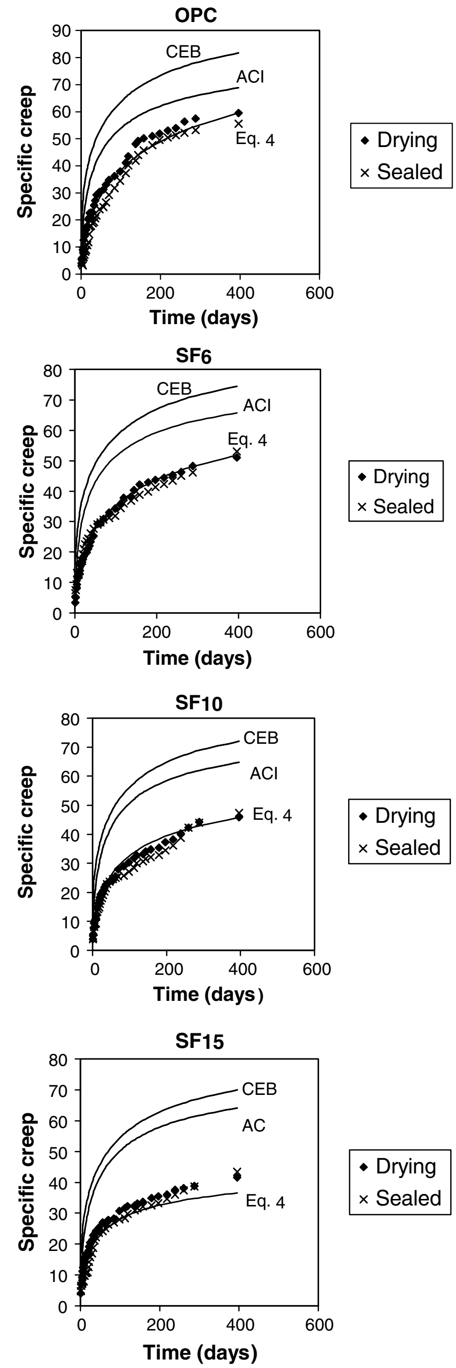

Fig. 3. Specific creep of specimens loaded at the age of 7 days (microstrain/MPa).

As shown in Figs. 3 and 4, Eq. (4) presents the creep of concrete containing different levels of silica fume much better than the ACI and CEB models. The error coefficients of Eq. (4), ACI [3] and CEB [4] prediction methods for specimens loaded at the age of 7 days were 6%, 36.6% and 52.6%, and also for specimens loaded at the age of 28 days were 8.9%, 27.2% and 47.8%, respectively. The ACI and CEB prediction equations are:

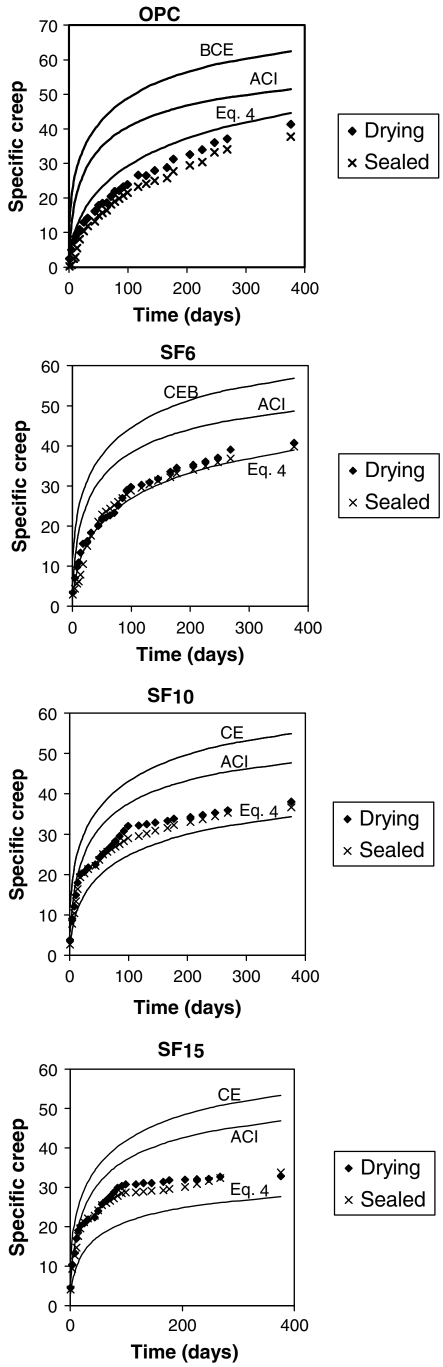

Fig. 4. Specific creep of specimens loaded at the age of 28 days (microstrain/MPa).

$$C(t) = 1/E(t) \ * \ (t^{0.6})/(10 + t^{0.6})\phi(u) \quad \text{(ACI209-92)}$$

where $\phi(u)$ = ultimate creep coefficient and

$$C(t) = 1/E(t = 28) \ * \ [t/(\beta_h + t)]^{0.3}\phi(u) \quad \text{(CEB-FIP1990)}$$

where β_h = shape function of the specimen.

Figs. 3 and 4 demonstrate that silica fume had a significant influence on the long-term creep. The final values for specimens loaded at the ages of 7 and 28 days are shown in Table 11. As the proportion of silica fume increased to 15%, the creep of concrete decreased by ≈20–30%. This finding is in agreement with the results of other investigators [7,41].

Table 11
Values of creep of 80 × 270 mm high specimens on completion of the tests (microstrain)

Age of loading (days)	Concrete mixes			
	OPC	SF6	SF10	SF15
7	595	510	459	417
28	413	407	381	328

4.7. Moisture movement

Moisture movement under alternating wetting and drying cycles is a common occurrence in practice. The magnitude of this cyclic moisture movement clearly depends upon the duration of the wetting and drying periods but since drying is very much slower than wetting, the consequence of prolonged dry weather can be reversed by a short period of rain. The movement also depends upon the range of relative humidity and the composition of the concrete, as well as the degree of hydration at the onset of initial drying. Experiments were conducted to investigate the influence of silica fume content on the moisture movement of high-strength concrete.

4.7.1. Shrinkage specimens

The shrinkage specimens of 80 × 270 mm height were submerged in water after 587 days of drying for a period of 60 days. Afterwards, they were removed and stored in a controlled environment of 20 ± 2 °C and 50 ± 5% relative humidity for 60 days. The results of these tests are shown in Table 12. The general effect of silica fume inclusion is to decrease moisture movement on the first wetting cycle, e.g. the SF15 mix recovered 34.2% of the 587 day-shrinkage compared with 37.6% for the OPC mix. The shrinkage of all specimens in the second drying cycle was similar for all mixes, and lower than their swelling in the second stage of the experiment. This could have been due to further hydration occurring

Table 12
Moisture movement of shrinkage specimens under alternating wetting and drying (microstrain)

Method of storage	Concrete mixes			
	OPC	SF6	SF10	SF15
587 days in air	532	528	523	512
60 days in water	200	192	185	175
60 days in air	155	150	144	140

during wet storage leading to increased physical and chemical bonds.

4.7.2. Creep specimens

The creep specimens were unloaded at the age of 403 days and their creep recovery was measured for 130 days. Almost all the creep recovery happened during the first month after unloading. After the recovery tests finished, all specimens were submerged in water for 60 days. Tables 13 and 14 show the results of the experiments. The creep recovery or reversible creep measured after unloading the unsealed specimens was ≈30% irrespective of SF content. It was apparent that the swelling caused by re-wetting of creep specimens stored for 60 days in water was more than that of shrinkage specimens. L'Hermite [42,43] agrees with this result and considers this additional recovery as an increase of swelling due to load. This finding establishes that water does play a significant role in the mechanism of creep.

4.7.3. Effect of loading on permeability

In order to investigate the effect of creep and shrinkage on the microstructure of concrete, it was decided to measure water penetration into the specimens after drying them. The water penetration test was performed by immersing the dry concrete cylinders for 24 h in water. The specimens were split in half by the indirect tensile test, and readings were taken to determine as to how far the water had penetrated into the concrete. Haque [44] has utilized this method to compare the water permeability of different concrete mixes previously. At least five readings were taken on each specimen and the average values of water penetration are included in Table 15. The maximum standard deviation of these readings was 0.79 mm. It is worth noting that a new more exact method has been developed recently for determining the water permeability of concrete [45].

It can be seen that as the proportion of silica fume increased, the 24-h water penetration decreased. This suggest an agreement with the previous experimental results [25] on the pore structure of mortars using mercury porosimetry technique which showed as silica fume content increased, the pore size distribution was shifted toward a finer distribution, the average pore size reduced and the porosity decreased. Also it is worth noting that the water penetration in the cover of swelling specimens was lower than that of shrinkage specimens, probably because of much longer period of wet curing in swelling specimens, resulting in a higher degree of hydration and lower porosity. However, in the creep specimens silica fume did not decrease the water penetration of the skin concrete but increased it in some circumstances. The 24-h water penetration of the skin concrete in all the specimens loaded at the age of 7 days was lower than that of the ones loaded at the age of 28 days.

Table 13
Moisture movement of creep specimens loaded at the age of 7 days under alternating wetting and drying (microstrain)

Method of storage	Concrete mixes			
	OPC	SF6	SF10	SF15
396 days under load	595	510	459	417
130 days after unloading	180	160	138	130
60 days in water	230	224	224	220

Table 14
Moisture movement of creep specimens loaded at the age of 28 days under alternating wetting and drying (microstrain)

Method of storage	Concrete mixes			
	OPC	SF6	SF10	SF15
376 days under load	413	407	381	328
130 days after unloading	125	122	114	100
60 days in water	210	200	190	185

Table 15
Water penetration into drying concrete (mm)

Kind of specimen	Concrete mixes			
	OPC	SF6	SF10	SF15
Creep ($t_0 = 7$ days)	6	5	7	7
Creep ($t_0 = 28$ days)	8	7	8	8
Shrinkage	11	7	7	7
Swelling	8	3	4	4

5. Conclusions

From the results presented in this paper, using concrete containing 0–15% silica fume, the main conclusions are:

1. In concrete mixtures with a constant slump of 100 ± 10 mm, those incorporating higher silica fume replacement levels tended to require more dosages of superplasticiser.
2. The compressive strength of concrete mixtures containing silica fume did not increase after the age of 90 days.
3. The modulus of elasticity–compressive strength relationship was similar to that of the ACI method. The modulus of elasticity at unloading the creep specimens was independent of silica fume content.
4. Silica fume did not affect the total shrinkage; however, as the proportion of silica fume increased, the autogenous shrinkage of high-strength concrete increased and its drying shrinkage decreased.

5. The total creep and basic creep were similar, and decreased as the level of silica fume replacement increased. Consequently, drying creep was negligible in the high-strength concrete specimens investigated here; hence, there was no interaction between creep and shrinkage, also specimen size and the relative humidity of the atmosphere had no effect on creep. The general effect of silica fume inclusion was to decrease moisture movement. On re-wetting of dried concrete using specimens having undergone shrinkage and creep, re-wetting caused more swelling in creep specimens than in shrinkage specimens. This finding suggests that water does play a significant role in the mechanism of creep.

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