TIME-DEPENDENT BEHAVIOUR OF CONCRETE COLUMNS CONTAINING SILICA FUME

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Abstract: *This paper presents the long-term deformations of reinforced high-strength concrete columns subjected to constant sustained axial forces. The objective of the study was to investigate the effects of binder systems containing different levels of silica fume on time-dependent behaviour of high-strength concrete columns. The experimental part of 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%, 8%, 10% and 15%. The mechanical properties evaluated in the laboratory were: compressive strength; secant modulus of elasticity; strain due to creep and shrinkage. The theoretical part of the work is about stress redistribution between concrete and steel reinforcement as a result of time-dependent behaviour of concrete. The technique used for including creep in the analysis of reinforced concrete columns was age-adjusted effective modulus method. The results of this research indicate that as the proportion of silica fume increased, the short-term mechanical properties of concrete 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) was negligible in this investigation. The results of the theoretical part of this research indicate that as the proportion of silica fume increased, the gradual transfer of load from the concrete to the reinforcement decreased and also the effect of steel bars in lowering the concrete deformation reduced. Moreover, the total strain of concrete columns decreased at higher silica fume replacement levels.*

Keywords: *high-strength concrete, silica fume, compressive strength, elastic modulus, creep and shrinkage*

1. INTRODUCTION

Nowadays high-strength and high-performance concrete is 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 hydroxide, which is 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 [1]. The advantages of utilizing high-strength concrete in columns are: their sections can be reduced in size; for the same cross-section, the amount of steel reinforcement can be reduced; in tall buildings, there is an economic advantage because of an increased floor area for rental.When a viscous-elastic material is subjected to a stress, from a time t_0, its strain, measured parallel to the axis of the stress, changes over time. This time-dependent increase in strain of hardened concrete subjected to sustained stress is called creep [2]. In reinforced concrete columns, creep results in a gradual transfer of load from the concrete to the reinforcement. In eccentrically loaded slender columns, creep increases the deflection

and can lead to buckling. In statically indeterminate structures, creep may relieve the stress concentration induced by shrinkage, temperature changes or movement of supports. In all concrete structures, creep reduces internal stresses due to non-uniform or restrained shrinkage so that there is a reduction in cracking. Another instance of the adverse effects of creep is in tall buildings in which differential creep between inner and outer columns may cause movement and cracking of partitions [3]. In high-strength concrete columns, 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 time-dependent behaviour of concrete. Therefore, to improve the durability of high-strength concrete columns, their creep and shrinkage should be addressed and necessary work should be implemented to control these deformations.This paper presents the time-dependent behaviour of high-strength concrete columns containing different levels of silica fume.

2. EXPERIMENTAL PART OF THE INVESTIGATION

2.1. Materials and mix proportions

The cementitious materials used were ordinary Portland cement (OPC), which is called Type I cement according to the ASTM description and silica fume (SF). Details of the mix proportions for the concrete containing different levels of silica fume are given in Table 1. 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 two 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.

2.2. Results and Discussion

2.2.1. Elastic Modulus

The results of secant modulus of concrete specimens containing different levels of silica fume, which were obtained in the creep tests, are shown in Table 2. 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 minutes; the stress/strength ratio was about 0.2. As shown in Table 2, increasing the silica fume replacement level increases the secant modulus of concrete.

Table 1. Mix proportions of concrete containing different levels of silica fume

Mix Components	Concrete Mixes				
	OPC	SF6	SF8	SF10	SF15
Cement (kg/m^3)	500	470	460	450	425
Silica fume (kg/m^3)	___	30	40	50	75
Gravel (kg/m^3)	1203	1203	1203	1203	1203
Sand (kg/m^3)	647	647	647	647	647
Water (kg/m^3)	175	175	175	175	175
W/b	0.35	0.35	0.35	0.35	0.35
Superplasticiser (kg/m^3)	8.17	9.78	10.62	11.71	13.34
28-day Strength (MPa)	58	65	68	67.5	70

Also the ACI Building Code 318-95 [4] has predicted the static modulus of the investigated specimens properly. This is in agreement with the previous findings [5]. It is worth noting that sealed and drying specimens had similar values of secant modulus. The ACI Building Code 318-95 [4] presents the following equation to calculate elastic modulus:

$E_c=4.7(f_c)^{0.5}$ (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. [6].

2.2.2. Shrinkage

ACI 209R-92 [7] and also CEB-FIP 1990 [8] committees have executed a lot of investigations to predict the shrinkage of concrete and presented good prediction methods for this phenomenon. However, as shown in figure 1, these methods do not really apply for the shrinkage of high-strength concrete containing silica fume. According to the experimental part of the work at early ages both methods tend to underestimate the shrinkage of drying specimens; nevertheless, at later ages, the CEB and ACI underestimate and overestimate total shrinkage respectively. It is worth noting that the cement content of all the specimens in the ACI method is assumed to be 500 kg/m^3. For the shrinkage determined in this investigation the following expression was developed:

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

where

$y = y_d = 1.14-0.007(V/S) \geq y_s$ (for drying specimens)

y= ys = 0.014SF+0.39(for sealed specimens)

SF = silica fume percentage

$\varepsilon_{sh}(t)$ = shrinkage after t days of drying

Fig. 1 demonstrates the improvements in predictions using equation 2 compared with those by the ACI [7] and CEB [8]. According to the experiments silica fume did not have considerable influence on drying specimens (total shrinkage). The average amount of total shrinkage after 587 days of drying was 524 microstrain with the standard deviations of 7.5. Moreover, silica fume considerably affected the shrinkage of sealed specimens. It is worth mentioning that the general effect of silica fume inclusion was to increase autogenous shrinkage. This is in agreement with the results of other researchers [9-13]. In other words, as the silica fume replacement level increased, the autogenous shrinkage of concrete increased. 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.

Table 2. 7- and 28-day compressive strength and secant modulus of elasticity

Concrete Mixes		Compressive Strength (MPa)	Measured Modulus (GPa)	Predicted Modulus by the ACI (GPa)
t_0=7 days	OPC	46	28.81	30.24
	SF6	50.5	31	31.69
	SF8	52	31.24	32.15
	Sf10	52	31.1	32.15
	SF15	53	31.5	32.46
t_0=28 days	OPC	58	34.4	34
	SF6	65	35.5	36
	SF8	68	37.25	36.77
	SF10	67.5	37	36.6
	SF15	70	38.1	37.3

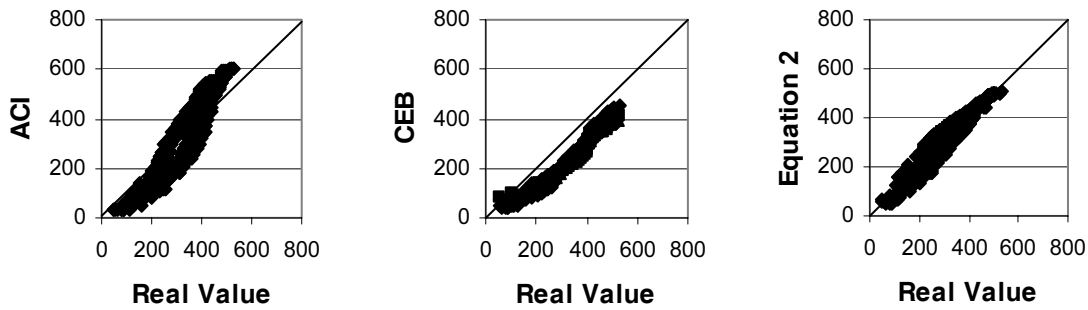

Fig. 1. Comparing different prediction methods for shrinkage in high-strength concrete (microstrain)

According to Sellevold [14] 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. The experimental results executed by Brooks et al. [15] 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 [16].

2.2.3. Creep

The results of specific creep, i.e. creep per unit stress, were studied for cylindrical specimens of 80*270 mm height, which were loaded at the ages of 7 and 28 days.

Because specimens were subjected to a sustained compressive stress of 10 MPa during all the creep tests, the real amounts of creep measured in the laboratory were 10 times more than the amounts of specific creep. It is worth mentioning that the above stress even in the weakest concrete of this research was lower than 30% of its compressive strength. It means the relationship between creep and load in all the specimens was linear [17,18].

The basic creep of sealed specimens, which had coated by aluminium waterproofing tape, was compared to the total creep of drying specimens. It can be said that the difference in creep of unsealed and sealed specimens was small in the control concrete and almost zero in the 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 [7] and CEB [8] methods are compared to the results of this investigation in Figure 2, which in fact shows that both methods overestimate the creep. For this investigation, a satisfactory model is expressed as follows:

$$C(t) = \frac{(t)^{0.6}}{(26.5 - SF) + (t)^{0.6}} * (103 - 3.65SF) * y * 10^{-6} \quad (3)$$

where

SF = silica fume percentage

C(t) = specific creep after t days of loading (microstrain / MPa)

$y = 1.08 - 0.0114\ t_0$

t_0 = loading age

As shown in fig. 2, equation 3 represents the creep of high-strength concrete containing different levels of silica fume much better than the ACI and CEB methods. Also it is worth noting that silica fume had a significant influence on lowering the long-term creep. This finding is in agreement with the results of other investigators [19,20]. The reason for the above decreasing may be because of higher compressive strength of concrete mixtures containing higher levels of silica fume at the age of loading because some researchers believe that higher compressive strength leads to lower creep [21-26].

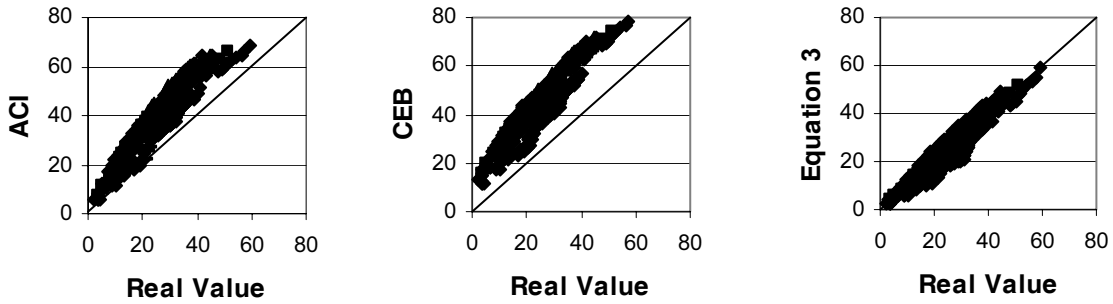

Fig. 2. Comparing different prediction methods for specific creep in high-strength concrete (microstrain/MPa)

3. THEORETICAL PART OF THE INVESTIGATION

3.1. Analysis of reinforced concrete columns

This part of the work focus on a symmetrically reinforced section subjected to a constant sustained axial force *P*. This load is resisted by the internal forces in the concrete and steel, $N_c(t)$ and $N_s(t)$. The redistribution of internal forces due to the gradual development of creep and shrinkage strains is to be examined and the time-dependent stresses and strains in both the concrete and the steel are to be calculated.

Equilibrium requires that, at any time, the sum of the internal forces equals the external load:

$$P= N_c(t) + N_s(t) \quad (4)$$

The compatibility requirements is that the total strain of reinforced column, concrete strain $\varepsilon(t)$ and steel strain $\varepsilon_s(t)$ are identical at all times:

$$\varepsilon(t) = \varepsilon_s(t) \quad (5)$$

The simplest and oldest technique for including creep in structure analysis is Faber's *Effective Modulus Method* [27]. If a concrete stress σ at a point in a structure remains constant with time, the total deformation at any time t after the application of load at time t_0 may be expressed as the sum of the instantaneous, creep and shrinkage components:

$$\varepsilon(t,t_0) = \varepsilon_e(t,t_0)+\varepsilon_c(t,t_0)+ \varepsilon_{sh}(t) =\sigma(t) /E_c(t_0)+ \sigma(t) /E_c(t_0).\phi(t,t_0)+ \varepsilon_{sh}(t) \quad (6)$$

If the instantaneous and creep components of strain in equation 6 are combined, a reduced or effective modulus for concrete $E_e(t,t_0)$can be defined as follows:

$$\varepsilon(t,t_0) = \sigma(t) /E_c(t_0).[1+ \phi(t,t_0)]+ \varepsilon_{sh}(t) = \sigma(t) /E_e(t,t_0) + \varepsilon_{sh}(t) \quad (7)$$

where $E_e(t,t_0)$ is $E_c(t_0)/[1+ \phi(t,t_0)]$.

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It is worth noting that creep is treated as a delayed elastic strain and is taken into account simply by reducing the elastic modulus for concrete. A time analysis using the *effective modulus method* is nothing more than an elastic analysis in which $E_e(t,t_0)$ is used instead of $E_c(t_0)$ [28].

The steel is assumed to be linear and elastic, with modulus E_s. Therefore, steel strain at any time t is:

$$\varepsilon_s(t)=\sigma_s(t)/E_s \quad (8)$$

From equation 4 it is clear that

$$P=\sigma(t). A_c + \sigma_s(t).A_s \quad (9)$$

and rearranging gives

$$\sigma_s(t)=[P- \sigma(t) A_c]/A_s \quad (10)$$

By substituting equations 7, 8 and 10 into equation 5 and simplifying, the concrete stress at time t may be found, as follows.

$$\sigma(t)/E_e(t,t_0) + \varepsilon_{sh}(t) =[P- \sigma(t) A_c]/(A_s.E_s) \quad (11)$$

and

$$\sigma(t) = \frac{P}{A_g.\{\rho.[n(t)-1]+1\}} - \frac{\varepsilon_{sh}(t).\rho.E_s}{\rho.[n(t)-1]+1} \quad (12)$$

where $A_g=A_c +A_s$; $\rho=A_s/A_g$; $n(t)=E_s/E_e(t)$.

With the concrete stress $\sigma(t)$ obtained from equation 12, the steel stress $\sigma_s(t)$ may be calculated using equation 10. The steel strain $\varepsilon_s(t)$ can be found using equation 8, which is identical to the total strain $\varepsilon(t)$ in accordance with equation 5.

In stress history of a concrete specimen either all the stress σ_o is suddenly applied at time t_0 and held constant with time or the stress $\sigma(t)$ is gradually applied, beginning at t_0 and reaching a magnitude equal to σ_o at time t_1. The creep strain at any time t after t_0 produced by the gradually applied stress is significantly smaller than that resulting from the suddenly applied

stress [28]. This is due to aging. A simple adjustment to the effective modulus method to account for aging of concrete was proposed by Trost [29]. Later the method was more rigorously formulated and further developed by Bazant [30]. This method is called the *age-adjusted effective modulus method*. It is worth noting that according to the experimental part of the work, the earlier the concrete specimens were loaded, the greater the final measured creep strains obtained. Therefore, if the stress is gradually applied, a reduced creep coefficient can be used to calculate creep strain. This reduced creep coefficient is $\phi(t,t_i).x(t,t_0)$. The coefficient $x(t,t_0)$ is called the *aging coefficient* and its magnitude gradually falls within the range 0.6 to 0.9 [28]. The creep strain at time t due to a stress $\sigma(t)$, which has been gradually applied over the time interval $t-t_0$, may be expressed as

$$\varepsilon_c(t,t_0) = \sigma(t)/E_c(t_0).\phi(t,t_0).x(t,t_0) \quad (13)$$

The initial stress σ_o of concrete in a reinforced concrete column, applied at time t_0, gradually reduces with time [3]. This change of stress is due to creep and shrinkage. The total strain at time t may be expressed as the sum of the instantaneous and creep strains produced by σ_o, the instantaneous and creep strains produced by the gradually applied stress increment $\Delta\sigma(t)$, and the shrinkage strain.

$$\varepsilon(t,t_0)=\sigma_o/E_c(t_0).[1+\phi(t,t_0)]+\Delta\sigma(t)/E_c(t_0).[1+\phi(t,t_0).x(t,t_0)]+\varepsilon_{sh}(t) \quad (14)$$

or

$$\varepsilon(t,t_0) = \sigma_o/E_e(t,t_0)+\Delta\sigma(t)/E_{ex}(t,t_0)+\varepsilon_{sh}(t) \quad (15)$$

where

$E_e(t,t_0)$ is the *effective modulus* of equation 7 and $E_{ex}(t,t_0)$ is the *age-adjusted effective modulus*, which is $E_c(t_0)/[1+\phi(t,t_0).x(t,t_0)]$.

3.2. Case study

To investigate the effect of silica fume on time-dependent behaviour of short columns, the analytical equations explained in part 3.1 and also equations 2 and 3 for predicting shrinkage and creep are utilized. In this part, it is assumed a Φ12 steel bar is embedded in the centerline of creep specimens. The elastic modulus and yield stress of the bar and also the applied load are assumed to be 210 GPa, 400 MPa and 50 kN respectively. According to Gilbert [28], the aging coefficients at the time of loading and 100 days or more after loading are 1 and 0.8 respectively. Fig. 3 shows the calculated strain of the columns with and without considering the effect of internal stress changes of concrete ($\Delta\sigma_c(t)$). It is clear that at the age of 100 days after loading or later the results of the two methods are almost the same. Consequently, to investigate the long-term effects of silica fume on the time-dependent behaviour of columns, the effect of internal stress changes of concrete can be neglected. The effect of silica fume on internal stresses at different ages is shown in fig. 4. It is clear that as the proportion of silica fume increases, the internal stress of concrete and steel bars, at all different ages, increases and decreases respectively.

Therefore, adding the proportion of silica fume makes the concrete part of the column more active; as a result, the gradual transfer of load from the concrete to the reinforcement lowers.

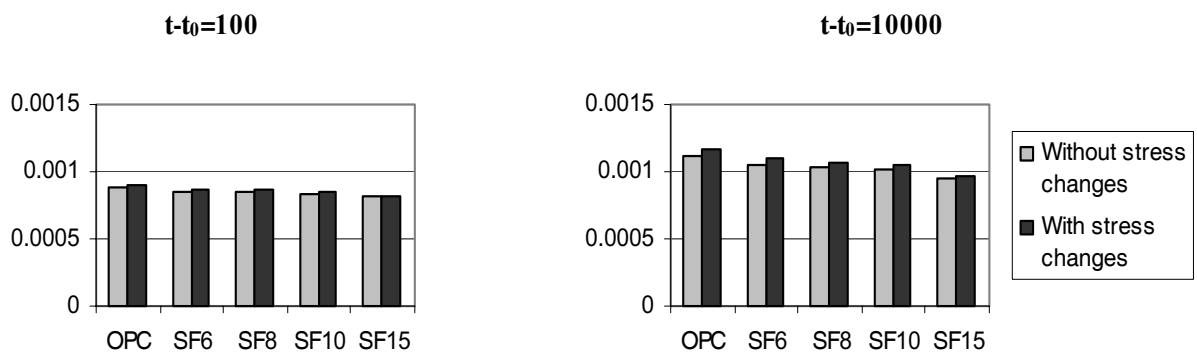

Fig. 3. Strain of the columns with and without considering the effect of internal stress changes of concrete

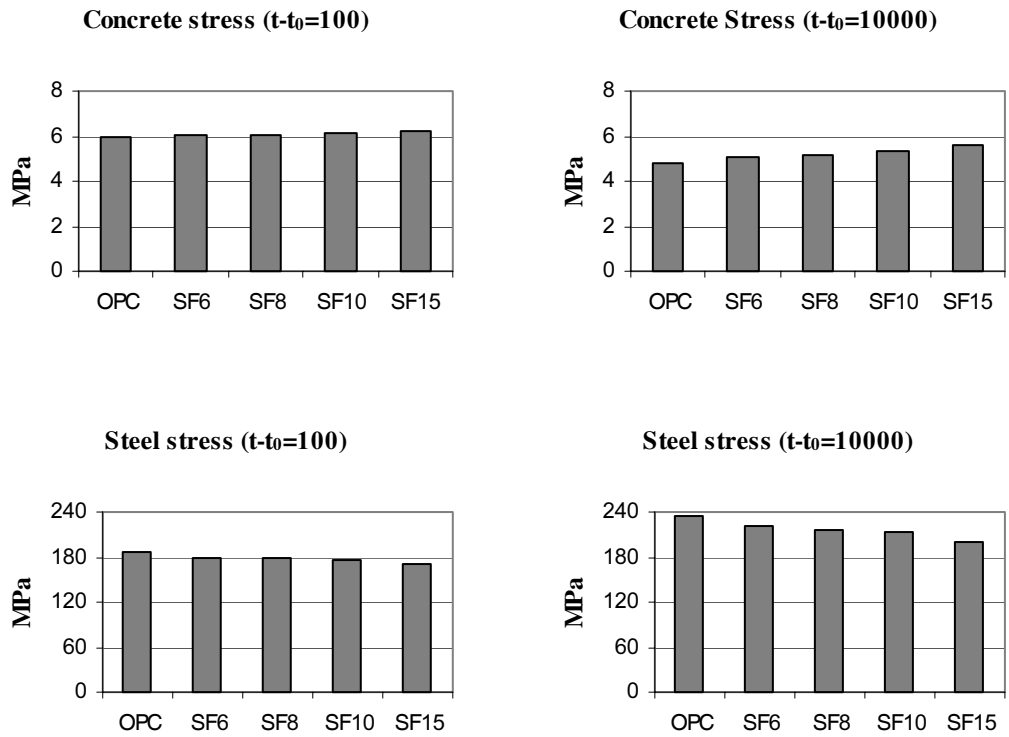

Fig. 4. Internal stresses of the concrete columns at different ages

For instance, 100 days after loading, the stress of the steel bar that is inside the specimen containing 15% silica fume is 9% lower than that of the one without silica fume.

This reduction is about 18% at the time of 10000 days after loading. Consequently, adding the proportion of silica fume to the mix is an effective method to reduce the stress of reinforcement over the time.

Fig. 5 shows the effect of silica fume on the strain of specimens with and without reinforcement. It is clear that, as expected, reinforcement reduces the deformation of specimens. Of coarse, it can be observed that increasing the proportion of silica fume decreases the effect of reinforcement on reducing the deformation of specimens. For instance, 100 days after loading, the deformation of reinforced specimens containing 15% and 0% silica fume is 79% and 75% of the ones without reinforcement respectively.

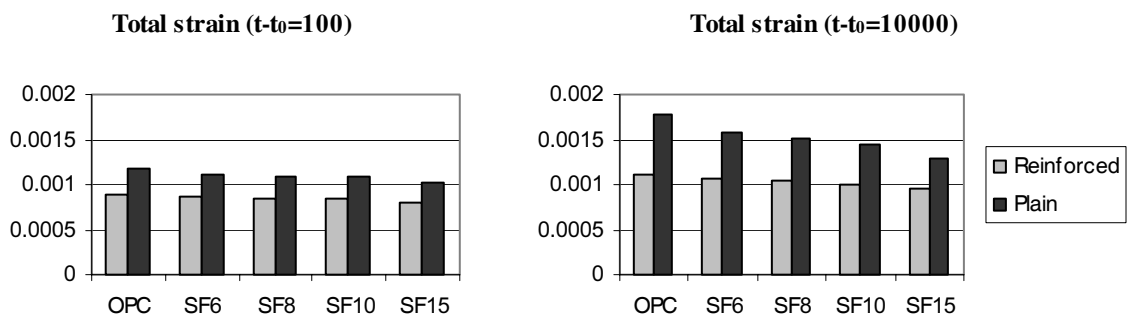

Fig. 5. Strain of the concrete columns at different ages

This reduction is 74% and 63% at the time of 10000 days after loading. In fact, this decrease is because of the effect of silica fume on reducing the gradual transfer of load from the concrete to the reinforcement. Another important point is that, in all circumstances, increasing the proportion of silica fume decreases the deformation of specimen. For example, 100 and 10000 days after loading, the deformation of specimen containing 15% silica fume is about 9% and 18% lower than the one without silica fume respectively. Consequently, silica fume can be used for strengthening columns against time-dependent deformation.

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