# 論文 Influence of Silica Fume on the Creep and Shrinkage of High-Strength Concrete

Ihab ADAM[*1], Toshiki AYANO[*2], Kenji SAKATA[*3]

**ABSTRACT:** This paper reports the results of an experimental investigation on the effect of silica fume content on creep and shrinkage behavior of high-strength concrete. Besides the control mix, three mixes incorporating silica fume as 5%, 10%, and 15% of the total cementitious materials (cement + silica fume), were prepared. Test specimens were dried and loaded at ages of 3, 7, and 14 days after casting. After preparation and load application, the specimens were transferred to two separate environmental rooms with 60% and 80% RH. According to this investigation, it is clear that the existence of silica fume considerably reduces the shrinkage strain and creep coefficient values.
**KEYWORDS:** Silica Fume, Creep, Shrinkage, High-Strength Concrete, Curing Period.

## 1. INTRODUCTION

Over the past years, there has been increased interest in the use of high-strength concrete, particularly in high rise buildings, long-span prestressed concrete bridges and offshore structures. The use of high-strength concrete demands lower water/cementitious ratio and higher cementitious materials content. Furthermore, it becomes common practice to use chemical and mineral admixtures in producing high-strength concrete. The particle-size distribution of a typical silica fume shows most particles to be smaller than one-micrometer (1μm) with an average diameter of about 0.1 μm; which is 100 times smaller than the average cement particle [1]. ACI Committee 234 [2] reported that for a 15% silica fume replacement of cement, there are approximately 2,000,000 particles of silica fume for each grain of cement in a concrete mixture. It is, therefore, no surprise that silica fume has a pronounced effect on concrete properties. In hardened concrete, silica fume increase the packing of the solid materials by filling the spaces between the cement grains in much the same way as cement fills the spaces between the fine aggregate particles, and fine aggregate fills the spaces between coarse aggregate particles in concrete. Hooton [3] have found that the addition of silica fume refines the pore size distribution of the cement paste. Shrinkage and creep of concrete caused by sustained load and moisture loss have a profound influence on cracking, long-term deflection and losses in prestressing [4]. It is therefore necessary to have a clear understanding of these deformations in concrete containing silica fume in order to predict its long-term behavior. Several studies have been carried out to study the elastic modulus, creep and shrinkage of concrete prepared with silica fume [3, 4, 5, 6, 7]. Yet the effect of silica fume on the creep and shrinkage of concrete is unclear and different researchers have presented conflicting results.

The purpose of the research reported here is to improve our understanding of the influence of inclusion of silica fume in concrete mixtures on the creep and shrinkage of high-strength concrete.

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[*1] Dept. of Environmental and Civil Engineering, Okayama University, Ph.D. student
[*2] Dept. of Environmental and Civil Engineering, Okayama University, Associate Prof.
[*3] Dept. of Environmental and Civil Engineering, Okayama University, Prof.

## 2. EXPERIMENTA L WORK

### 2.1 MATERIALS

Ordinary portland cement (specific gravity: 3.15) and silica fume (specific gravity: 2.2) were used as cementitious materials. Fine aggregate was river sand (with specific gravity: 2.62 and water absorption: 1.69%), whereas coarse aggregate was crushed stone (with specific gravity: 2.75 and water absorption: 0.52%) with nominal maximum size of 20 mm. The physical properties of both fine and coarse aggregates were measured according to the relevant Japanese Industrial Standard. All aggregates were used wet in all concrete mixtures, and corrections were made to take into account the water on the surface of the aggregate particles. Chemical admixture was a naphthalene-based Superplasticizer, which was added as 3.5% of the total cementitious materials content and was included in the calculation of water/cementitious ratio [8].

### 2.2 MIX PROPORTIONS

Mix proportions were basically the same for all concrete mixtures. The only difference between the mixes is the silica fume content. These proportions, together with the test conditions, are summarized in Table 1. Water content given in Table 1 includes the superplasticizer and the amount of water from the aggregates that exceeds their absorption. The control mix (0% SF) was proportioned to have a water/cement ratio of 0.20. The three silica fume concrete mixtures incorporated 5%, 10%, 15% silica fume by mass as a partial replacement for portland cement. The water/cementitious ratio and water content were kept the same as for the control concrete, regardless any changes in slump. This was done in order to maintain a constant water/cementitious ratio of 0.20 for all mixtures. The lower specific gravity of silica fume compared with that of portland cement means that when replacement is based on mass, a larger volume of silica fume is added than the volume of cement removed. Thus, the volume of paste increases [1]. To keep the same yield of mortar volume for all concrete mixtures, sand proportion was decreased in the concrete mixtures containing silica fume.

Table 1 Concrete Mixture Proportions and Test Conditions

| Mix | | Weight per unit volume ($kg/m^3$) | | | | | | Note | |
|---|---|---|---|---|---|---|---|---|---|
| | w/c | W | C | SF | S | G | SP | Curing period | Test RH% |
| Control | | | 700 | 0 | 606 | | | 14 days | 60% |
| 5% SF | | | 665 | 35 | 593 | | | | |
| 10% SF | 0.20 | 140 | 630 | 70 | 581 | 1063 | 24.5 | | |
| 15% SF | | | 595 | 105 | 568 | | | 3, 7, 14 days | 60% & 80% |

### 2.3 MIXING PROCEDURE

Buttering of the mixer (disposal of the first mix) was always carried out before the first intended mix was prepared on the day of casting. The same mixing procedure was used for all concrete mixtures. The cement and silica fume were first blended together, outside the mixer, until a homogeneous color was obtained. Then the blend was added to the mixer followed by water and mixed for 2 minutes. The sand and superplasticizer were successively added and mixed for 1 and 4 minutes, respectively. Finally, gravel was added to the other constituents and mixed for 1 minute.

Fresh mix was released from the mixer and all prisms and cylinder moulds were then filled at two and three layer, respectively; each layer was compacted on a vibrating table until the layer surface shows slight traces of bleeding. Immediately after casting, the open surface of the specimens was covered with a plastic sheet (to reduce the rate of water evaporation) and all specimens were then placed in a curing room with 60% relative humidity and a temperature of 20C. The moulds were removed after 24 hours and the specimens were cured in water, at 20C, until testing at 3, 7, and 14 days.

### 2.4 SPECIMENS AND TEST CONDITIONS

The dimensions of specimens for compressive strength and modulus of elasticity tests were 100 x 200-mm cylinders. Testing was carried out on groups of three cylinders in accordance with the JIS A 1108 test method. The ends of the cylinders were ground before testing.

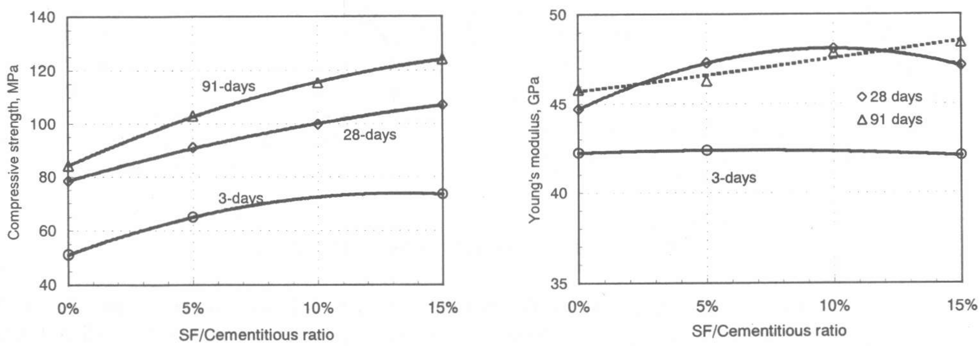
Creep and shrinkage tests were performed on prisms 100 x 100 x 400-mm over an effective gauge length of 250-mm using the Whittemore strain gauge whose minimum reading is 1/1000 mm. The reported shrinkage and creep values represent the results of the average of two identical specimens. The samples were cured in water till the age of test (14 days) and thereafter stored under standard laboratory conditions in a controlled temperature (20C) and relative humidity (60%). However, concrete specimens contains 15% silica fume were tested at three ages, i.e. 3, 7 and 14 days. Those specimens tested at 14 days were kept in two different environmental rooms with 60% and 80% relative humidity. All creep samples were subjected to a nominal stress of 30% of the concrete compressive strength at the moment of loading.

## 3. RESULTS AND DISCUSSION

### 3.1 EFFECT OF SILICA FUME

(1) Compressive strength and elastic modulus

The strength of the composite material is not only dependent on the relative proportions of the components (in concrete, the proportion of water, cement and aggregates) but also on the strength of the bond between these components [9]. The addition of silica fume to the concrete appears to improve that bond. The variation of the compressive strength values of concrete prepared with and without silica fume under continuous water curing is shown in Fig. 1(a). Comparing the compressive




(a) compressive strength (b) Young's modulus

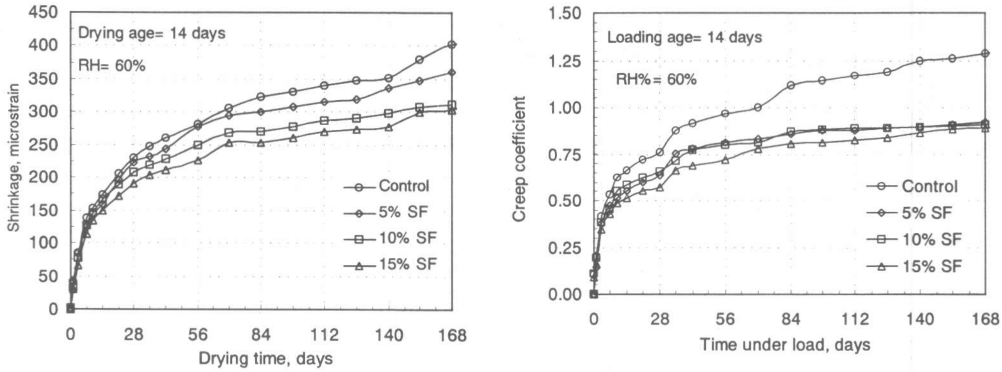
Fig. 1 Variation of compressive strength and Young's modulus with Silica fume content

strength of control concrete (0% SF) and silica fume concrete, it is clear that replacement of portland cement with silica fume improves the strength at all ages and the silica fume contributes to the strength from as early as the age of 3 days. It has been established that the silica fume starts to contribute to the strength as early as the age of one day and accelerates the hydration of cement during the early stages [3, 9, 10]. After 91 days of water curing, the compressive strength of the silica fume mixes were 22% to 48% higher than the control mix, with higher increases as silica fume contents were increased.

Elastic modului were measured, for silica fume and non-silica fume concretes, at different ages using compressometer with 100-mm gauge length and are shown in Fig. 1(b). ACI committee 234 [10] stated that the modulus of elasticity and stress-strain behavior of silica fume concrete are apparently similar to those of portland cement concrete of similar strength. The elastic moduli of silica fume concrete mixes were marginally higher than that of the control mix, particularly at ages earlier than 28 days. The increase in the elastic moduli is more pronounced at ages greater than 28 days as shown in Fig. 1(b). However elastic moduli of concretes were found to increase with increasing compressive strength, this agrees with the findings of Khatri el al. [7] and Hooton [3].

(2) Shrinkage and Creep

The shrinkage strain development with time of all concrete mixtures is shown in Fig. 2(a). This group of specimens was cured in water till the age of 14 days and thereafter was kept under constant temperature of 20C and relative humidity of 60%. It is evident from the figure that the existence of silica fume reduces the shrinkage strain of concrete prepared with portland cement, particularly after the period of 28 days after drying. Khatri el al. [7] found the same result, however, they observed that 10% silica fume increases the early age shrinkage (up to 28 days) of non-silica fume concrete with the same water/cementitious ratio and cementitious materials content. It has been found that strain due to both creep and shrinkage is caused by removal of the adsorbed water [5]. In the case of shrinkage the cause of removal of water is the ambient relative humidity and in the case of creep the cause is the applied stress. Because of the decrease in the number of coarse pores, silica fume concrete is less permeable [3]. This, consequently, could reduce the rate of the drying shrinkage, since it will take more time for the water to find its way out of the specimen.



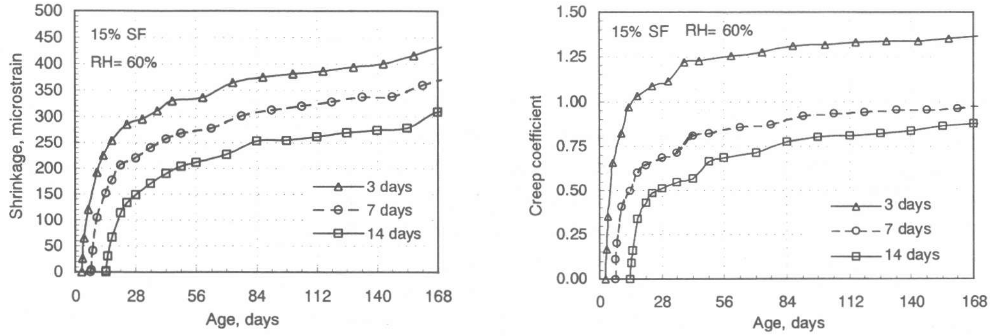

(a) shrinkage (b) creep

Fig. 2 Effect of silica fume on shrinkage and creep

Figure 2(b) depicts the creep coefficient of all concrete mixtures. It can be observed that the silica fume considerably reduces the creep coefficient of concrete. Concrete contains 5% silica fume experienced almost the same creep coefficient values as that of concrete contains 10% silica fume for the whole test period. After 168 days under drying, creep coefficient values of concrete contains 5%, 10%, and 15% silica fume were 72%, 71%, and 69% of that of the control mix, respectively. Creep is affected by the microstructure of the transition zone of concrete [7]. Based on the studies carried out on mortar [9], it was concluded that the addition of silica fume improves the transition zone and this could be also responsible for the decrease in creep strain by the addition of silica fume to ordinary portland cement concrete.

## 3.2 EFFECT OF CURING PERIOD

Figure 3(a) shows the development of shrinkage strain of concrete containing 15% silica fume in the environmentally controlled room (RH=60%) after water-curing for different lengths of time i.e. different ages of concrete at the start of drying. It could be noticed that water-curing for 14 days could significantly reduce the shrinkage strain of silica fume concrete. The 168-day shrinkage for the specimens cured under water for 14 days before drying is 72% of the corresponding shrinkage for the specimens, which were initially water-cured for only 3 days. The shorter the curing period the faster the rate of shrinkage development, particularly during the first two weeks after drying.



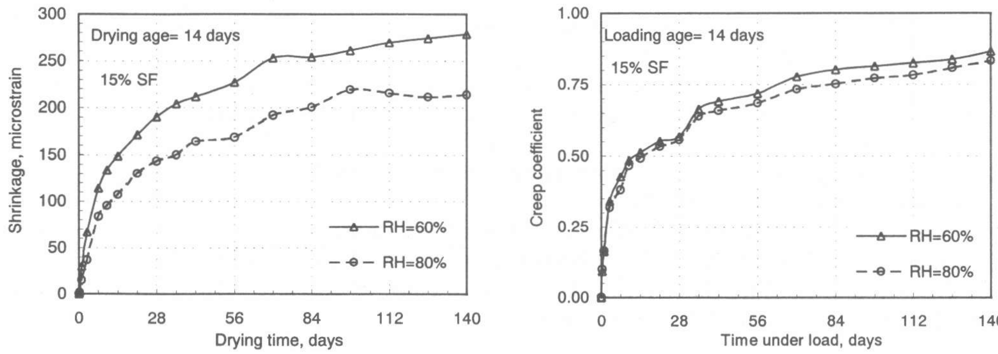

(a) shrinkage (b) creep

Fig. 3 Effect of initial water-curing period on shrinkage and creep

The effect of the initial water-curing period (the age of concrete at loading) on creep coefficient of silica fume concrete is shown in Fig. 3(b). As expected, the creep coefficient decreases with increase in the age at the time of loading. After 168 days under load, the creep coefficient of concrete loaded at 3 days is 40% and 54% higher than that of concrete loaded at 7 and 14 days, respectively. The rate of creep during the first few weeks under load is much greater for concrete loaded at 3 days than for older concretes. For concrete loaded at the age of 3 days, creep coefficient after 3 weeks under load attained about 80% of its value at the end of the test period (168 days).

### 3.3 EFFECT OF HUMIDITY CONDITIONS

Specimens prepared from concrete mix containing 15 % silica fume were cured in water for 14 days after casting, then loaded and dried and transferred to two separate environmental rooms with 60% and 80% relative humidity.




(a) shrinkage (b) creep

Fig. 4 Effect of ambient RH% on shrinkage and creep

The development of both shrinkage and creep coefficient values with time of these specimens is presented in Fig. 4. From this figure it is clear that the lower the relative humidity of the surrounding medium, the greater the shrinkage and creep coefficient values. However, the ambient relative humidity has a more profound effect on shrinkage of silica fume concrete than its effect on creep coefficient. After 140 days drying period, shrinkage for 60% relative humidity was 1.3 times that at

80% relative humidity. The relative humidity has little influence on the development rates of shrinkage strain and creep coefficient of silica fume concrete.

## 4. CONCLUSIONS

The present study investigating the effect of silica fume content on shrinkage and creep of high-strength concrete led to the following conclusions. The replacement of portland cement by silica fume along with the use of a sufficient amount of Superplasticizer, increases the concrete compressive strength. Strength of silica fume concrete increases with increasing silica fume content. The addition of silica fume considerably reduces the strain due to creep and shrinkage of concrete. The shrinkage strain is affected by the initial water-curing period, the longer the water-curing period, the smaller the shrinkage strain. Creep coefficient is affected by the loading age, which is a significant factor in the development of creep. Creep develops very fast when loaded at early ages and stabilizes after few weeks. Increase in relative humidity results in decrease in shrinkage strain and creep coefficient values.

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