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ScienceDirect
Cement & Concrete Composites 30 (2008) 316–326
Cement & Concrete Composites
www.elsevier.com/locate/cemconcomp

# Estimating long-term creep and shrinkage of high-strength concrete

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Received 14 March 2006; received in revised form 23 September 2007; accepted 24 September 2007
Available online 29 September 2007

**Abstract**

This paper presents the development of formulas to estimate the long-term creep and shrinkage of high-strength concrete. 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%. According to the experimental results some equations are proposed for predicting the time-dependent behaviour of high-strength concrete. Based upon a survey of published experimental data, the accuracy of the proposed equations compares favorably with that of several common methods, which were developed for estimating the creep and shrinkage of normal strength concrete. Also, according to the experimental work, it is shown that to improve the estimation of long-term deformations of high-strength concrete utilizing the ACI and CEB methods, the results of short-term tests should be substituted into them.

*Keywords:* High-strength concrete; Silica fume; Creep; Shrinkage; Elastic modulus; Modeling

## 1. Introduction

The importance of creep and shrinkage is significant in that each, depending upon the concrete maturity at loading, can be two to four times larger than the elastic strain [1]. The problem of exact predicting the long-term deformations of high-strength concrete remains too. In fact, reliable estimation according to the existing models is not possible because they are developed for ordinary concrete and also the influence of aggregate cannot be estimated without tests. Therefore, it is desirable to develop means of estimating long-term deformations from short-term tests. In other words, if very accurate predictions of deformations are required, the long-term behaviour must be extrapolated, using an assumed time function, from creep and shrinkage tests performed on the prototype concrete. However, relatively simple prediction equations are required for design when the only factors known to the design engineer are specified concrete strength, age of loading, probable ambient humidity and the volume to surface ratio of the member.

Clearly, the accuracy of the prediction of creep and shrinkage depends upon the form of the time function used. Neville et al. [2] have reviewed the various types of equations generally used, which are: power expression, logarithmic expression, exponential expression and hyperbolic expression. A combined power and hyperbolic form, suggested by Branson et al. [3], is also of interest. The present paper suggests improved prediction expressions derived from experimental results obtained by the author and verified against the test results of other investigators. It is worth noting that the final prediction expressions were published earlier [4]; however, they were not verified based upon a survey of the published experimental data. Also some recommendations are suggested for improving the exactness of the existing models for predicting the long-term creep and shrinkage of high-strength concrete.

## 2. Experimental details

The cementitious materials used were ordinary Portland cement (OPC) and silica fume (SF), their chemical compo-

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doi:10.1016/j.cemconcomp.2007.09.006

sitions 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. For each mix, the following specimens were made: 24 100 mm cubes for compressive strength; eight 80 × 270 (diameter × length) mm cylinders for creep; four 80 × 270 mm and four 150 × 300 mm cylinders for shrinkage. The details of the experimental work including the actual mixes used, test procedures and the spread of the results were published earlier [4].

## 3. Modeling

The equation used by the author for predicting the creep of the investigated concrete mixes is a hyperbolic-power expression as follows:

$$C(t,t_0) = \frac{(t-t_0)^{\mathrm{d}}}{A\cdot(t-t_0)^{\mathrm{d}}+B} \tag{1}$$

or

$$Y = A\cdot X + B \tag{2}$$

where $X = (t-t_0)^{\mathrm{d}}$, $Y = (t-t_0)^{\mathrm{d}}/C(t,t_0)$, $(t-t_0)$ is duration of loading and $t_0$ is loading age. The same equation is utilized for predicting the shrinkage of the concrete mixes. According to the experimental data, the values $X$ and $Y$ can be measured at each time. A plot of $Y$ against $X$ gives a straight line of slope $A$, and the intercept on the ordinate is equal to $B$. In this stage, Eq. (2) can be drawn after assuming a specific value for $d$. In fact, $d$ is a constant power and if $d = 1$, Eq. (1) becomes a simple hyperbolic expression. The experimental results published earlier [4] show that the suggestions of ACI committee 209-92 [5] for $d$ are applicable for the creep and shrinkage of high-strength concrete. These values are 0.6 and 1, respectively. According to Eq. (1) when $(t-t_0)\to\infty$, the limiting specific creep $C_u \to 1/A$ and thus the limiting creep can be obtained directly from experimental results. Therefore:

$$C(t,t_0) = \frac{(t-t_0)^{0.6}}{(t-t_0)^{0.6}+B\cdot C_{\mathrm{u}}}\cdot C_{\mathrm{u}} \tag{3}$$

It can be seen when $B\cdot C_{\mathrm{u}} \to (t-t_0)^{0.6}$, one-half of the ultimate creep is expected to occur. This means, considering the time-dependent behaviour of concrete, both $A$ and $B$ are meaningful and each of them shows a specific characteristic of concrete. All these parameters for the specimens loaded at the age of 7 days are given in Table 3. According to this table, the relation between ultimate specific creep and the proportion of silica fume can be found utilizing regression analysis as follows:

$$C_{\mathrm{u}} = -3.65\mathrm{SF} + 103 \quad (R^2 = 0.9314) \tag{4}$$

where SF is the percentage of silica fume replaced cement. It is clear that as the proportion of silica fume increased, the ultimate creep decreased. This may happen because of improving the strength of concrete at the age of loading as a result of increasing the silica fume replacement level. In fact, some researchers believe that specimens having higher compressive strength show lower creep [6–8]. Also the relation between $B\cdot C_{\mathrm{u}}$ and the proportion of silica fume can be obtained in a similar manner as follows:

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 | SF8 | SF10 | SF15 |
| Cement (kg/$m^3$) | 500 | 470 | 460 | 450 | 425 |
| Silica fume (kg/$m^3$) | 0 | 30 | 40 | 50 | 75 |
| Superplasticiser (kg/$m^3$) | 8.17 | 9.78 | 10.62 | 11.71 | 13.34 |

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

Table 3
Creep parameters of the specimens loaded at the age of 7 days

| Mix components | Concrete mixes | | | | |
|---|---|---|---|---|---|
| | OPC | SF6 | SF8 | SF10 | SF15 |
| $B$ | 0.2387 | 0.2703 | 0.2868 | 0.2573 | 0.2096 |
| $A$ | 0.0095 | 0.0117 | 0.0153 | 0.0155 | 0.0190 |
| $R^2$ | 0.9795 | 0.9893 | 0.9846 | 0.9815 | 0.9954 |
| $C_{\mathrm{u}} = 1/A$ | 105.26 | 85.47 | 65.36 | 64.52 | 52.63 |
| $B\cdot C_{\mathrm{u}}$ | 25.11 | 23.1 | 18.75 | 16.60 | 11.03 |