Adjustment of B3 model for drying concrete with additives based on experimental data

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Abstract: All currently available concrete creep predicting models cannot describe well the creep of a concrete structure because they all leave the effects of additives out of consideration. The purpose of this work was to modify model B3 for overcoming this deficiency. We tested thirteen specimens of C40 and C50 concrete with additives, out of which nine were for creep and four for shrinkage tests over a 700 d period under controlled temperature. We compared the experimental results for creep and shrinkage with those obtained by using model B3, and derived modification terms through regression analysis. Based on the experimental results of identical specimens under varied stress levels, we also derived a function considering the effect of stress level on creep. It is suggested that the creep prediction models without adjustment should not be used for modern concrete with a variety of additives.

Keywords: stress strength ratio; creep test; B3 model; regression analysis

1 Introduction

Concrete creep strain is usually more than two times larger than instantaneous strain; thus, if an analyst is concerned about deflections, deformations, stiffness and internal force distribution due to long term loads, he must primarily look into creep and its mechanism [1]. While surveying research on concrete creep, it can be clearly understood that a wealth of experimental data have been accumulated. Based on those experimental data, there have been some codes developed, for example, ACI-209(1992) [2], B3 [3], CEB-FIP (1978) [4], CEB-FIP (1990) [5] and GL 2000 [6]. There are thousands of research articles on creep of concrete which are referred to in Ref. [7]. Despite the research on creep of concrete starting at the beginning of the 19th century [8], there has not been an ideal code which can predict creep of all types of concrete and structures being used [9]. Because of the variability nature of concrete and complexity of creep phenomenon, forming such codes is out of question [10]. However, it is recognized that there are some serious problems in current codes, the effect of which should be rectified.

Due to the shortcomings of models to predict creep and the extremely heterogeneous nature of concrete, these models cannot perfectly predict the creep rate of all types of concrete. Some of the prediction models fail to consider all parameters that may likely affect creep of concrete. Considering the case of a very popular creep model, ACI-209(92) as an example, the creep coefficient is a function of slump, air content, s/a (ratio of fine aggregate to total aggregate), curing condition, and specimen dimensions. It has no indication of effect of cement amount, w/c ratio, a/c ratio (aggregate cement ratio), strength of concrete, etc. Two batches of concrete having the same slump, air content and s/a ratio can vary in strength, aggregate content, w/c ratio, etc. However, according to ACI model, their creep coefficients are the same, which are quite questionable. The prediction model B3 is calibrated with a
computerized data bank comprising practically all the relevant test data obtained in various laboratories throughout the world. Besides, the parameters chosen for creep prediction in B3 model are more relevant compared with the ACI-209 (1992) model. However, similar to ACI model, there in B3 model is no consideration of the effects of super-plasticizers and additives in concrete, which calls modification.

Today’s concrete is quite different from that in the mid 19th century. With the development of concrete with higher slump and better cohesion, the construction method has changed. These days, we pump concrete of high slump from the springing to the crown of a concrete filled steel tubular (CFST) arch bridge [11]. The same method is being adopted in the case of high rise buildings and many other structures. In other words, the majority of today’s concrete uses many types of additives (such as fly ash and silica fume) and super-plasticizers to increase its performance. For modern construction, admixtures have been a necessary component of concrete. However, all creep models widely used leave additives out of consideration. Thus, when using existing creep models for creep prediction of modern structures, modification is necessary.

Because of the extremely heterogeneous structure of concrete, theoretical approximation is not enough for predicting concrete creep with a model. Therefore, it is reasonable to use experimental method to understand the creep rate and creep quantity of concrete with admixtures. With an attempt to solve the problems aforementioned, we conducted an experimental study to obtain the data about the creep of sealed concrete with additives, and modified the existing B3 model based on the comparison of observed and calculated data.

2 Experimental details

An experimental program was organized to quantify creep of drying concrete (drying refers to concrete which are not sealed) and to understand the effect of stress strength ratio on creep magnitude. The number of specimens, specimen dimension, concrete types, stress strength ratios, etc. were chosen as main parameters affecting creep. Shrinkage test was performed on identical specimens so that creep and shrinkage could be isolated on the assumption that the superposition principle is allowed. Measures were applied to have the test results within the accuracy of the instrument. All specimens were kept in a room with controlled temperature; further caution was applied to reduce error in measurement using precision thermometer, thus every dial gauge reading due to temperature change was calculated and subtracted from the test results.

2.1 Specimen design

Dimensions of specimen were chosen such that creep deformation could be measured well (the longer the specimen, the easier to measure creep strain of larger deformation) and there would be less chance of failure in buckling while applying sustained load up to 60% of the ultimate strength. From trial and error method, 1 200 mm length and 140 mm diameter were chosen for all specimens. Two dial gauges were mounted on each specimen so that the observed result would be more reliable (possible error due to dial gauge could be addressed). A loading frame was designed and tested. Four prestressed bars of a 32 mm diameter were used to apply sustained load on each specimen. From the preliminary test, the use of a loading frame to apply sustained load was confirmed. Special wrenches were designed so that a load could be applied manually with a lengthened lever arm. Thirteen specimens were prepared for creep and shrinkage tests and their properties are listed in Table 1. The specimen name C40-18-20D implies that this specimen was made of concrete type C40 which was sealed and a load of 20% of its capacity was imposed on at the age of 18 days after mixing. Similarly, C40-SH-18-D implies that the specimen was a drying one exposed to shrinkage after 18 days of maturity.

2.2 Materials

The compositions of the concrete mixture were as listed in Table 2. The Young’s modulus of concrete for specimens with dimensions of 150 mm×150 mm×300 mm was 34 GPa for C50 and 29 GPa for C40.

2.3 Strength test of PCC (plain concrete column) specimens

Three PCC specimens with identical dimensions and varying concrete grade were tested for 28 d ultimate strength. Then, a load of respectively 20% and 40% of the capacity was applied as a sustained load on a specimen for creep tests. Longitudinal strain and lateral strain produced at the mid span of the column were obtained from the strain gauges in respective directions.
Table 1 Specifications of specimens, where $N$ is the applied load, $N_u$ is the ultimate strength, $t_0$ is the loading age, and N/A refers to not applicable

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Specimen</th>
<th>Load/kN</th>
<th>$N/N_u$</th>
<th>Concrete</th>
<th>$t_0$/d</th>
<th>Temperature/°C</th>
<th>Relative humidity/%</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C40-18-20D</td>
<td>100.4</td>
<td>0.2</td>
<td>C40</td>
<td>18</td>
<td>25</td>
<td>65</td>
<td>Creep</td>
</tr>
<tr>
<td>2</td>
<td>C40-18-40D</td>
<td>200.8</td>
<td>0.4</td>
<td>C40</td>
<td>18</td>
<td>25</td>
<td>65</td>
<td>Creep</td>
</tr>
<tr>
<td>3</td>
<td>C40-28-20D</td>
<td>100.4</td>
<td>0.2</td>
<td>C40</td>
<td>28</td>
<td>25</td>
<td>65</td>
<td>Creep</td>
</tr>
<tr>
<td>4</td>
<td>C40-28-40D</td>
<td>200.8</td>
<td>0.4</td>
<td>C40</td>
<td>28</td>
<td>25</td>
<td>65</td>
<td>Creep</td>
</tr>
<tr>
<td>5</td>
<td>C40-SH-18-D</td>
<td>0.0</td>
<td>N/A</td>
<td>C40</td>
<td>18</td>
<td>25</td>
<td>65</td>
<td>Shrinkage</td>
</tr>
<tr>
<td>6</td>
<td>C40-SH-28-D</td>
<td>0.0</td>
<td>N/A</td>
<td>C40</td>
<td>28</td>
<td>25</td>
<td>65</td>
<td>Shrinkage</td>
</tr>
<tr>
<td>7</td>
<td>C50-18-20D</td>
<td>133.0</td>
<td>0.2</td>
<td>C50</td>
<td>18</td>
<td>25</td>
<td>65</td>
<td>Creep</td>
</tr>
<tr>
<td>8</td>
<td>C50-18-40D</td>
<td>266.0</td>
<td>0.4</td>
<td>C50</td>
<td>18</td>
<td>25</td>
<td>65</td>
<td>Creep</td>
</tr>
<tr>
<td>9</td>
<td>C50-28-20D</td>
<td>133.0</td>
<td>0.2</td>
<td>C50</td>
<td>28</td>
<td>25</td>
<td>65</td>
<td>Creep</td>
</tr>
<tr>
<td>10</td>
<td>C50-28-40D</td>
<td>266.0</td>
<td>0.4</td>
<td>C50</td>
<td>28</td>
<td>25</td>
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<td>Creep</td>
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<td>11</td>
<td>C50-SH-18-D</td>
<td>0.0</td>
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<td>25</td>
<td>65</td>
<td>Shrinkage</td>
</tr>
<tr>
<td>12</td>
<td>C50-SH-28-D</td>
<td>0.0</td>
<td>N/A</td>
<td>C50</td>
<td>28</td>
<td>25</td>
<td>65</td>
<td>Shrinkage</td>
</tr>
<tr>
<td>13</td>
<td>C40-18-60D</td>
<td>301.2</td>
<td>0.6</td>
<td>C40</td>
<td>18</td>
<td>25</td>
<td>65</td>
<td>Creep</td>
</tr>
</tbody>
</table>

Table 2 Ingredients and properties of tested concrete

<table>
<thead>
<tr>
<th>Concrete type</th>
<th>Cement Content/(kg $m^{-3}$)</th>
<th>Coarse aggregate</th>
<th>Sand</th>
<th>Water</th>
<th>Super-plasticizer</th>
<th>Fly ash</th>
<th>Density/(kg $m^{-3}$)</th>
<th>Mean strength/MPa</th>
<th>Sample size</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>C40</td>
<td>347</td>
<td>1 149</td>
<td>720</td>
<td>167</td>
<td>6</td>
<td>72</td>
<td>2 460</td>
<td>46</td>
<td>35</td>
<td>0.12</td>
</tr>
<tr>
<td>C50</td>
<td>470</td>
<td>1 050</td>
<td>670</td>
<td>150</td>
<td>9</td>
<td>71</td>
<td>2 420</td>
<td>63</td>
<td>35</td>
<td>0.09</td>
</tr>
</tbody>
</table>

The ultimate strength of C40 concrete PCC specimens was 502 kN, and that of C50 was 665 kN. The instantaneous strain under a load of 20% capacity was 186.2×10⁻⁶ for C40 and 189.7×10⁻⁶ for C50; and that under a load of 40% capacity was 383.1×10⁻⁶ for C40 and 409.7×10⁻⁶ for C50.

2.5 Creep test (basic creep plus drying creep)

Nine specimens were tested for creep. The actual temperature and humidity in the test room were measured regularly and tried to maintain constant as far as possible. Fig. 1 shows a typical drying plain concrete specimen during a creep and a shrinkage test, respectively. Considering that specimens shrink during the creep test, the shrinkage was also recorded for computing the net creep strain with. Fig. 2 shows the specimens and the loading system for the creep test.

Fig. 1 Drying plain concrete specimens for (a) creep test and (b) shrinkage test

2.6 Shrinkage test

Fig. 1b depicts a drying plain concrete specimen
during a shrinkage test. Before the shrinkage test, the specimen was kept in a steel casing, and was assumed to have only autogenous shrinkage. The shrinkage of specimens C40-SH-18-D and C50-SH-18-D was recorded at the age of 18 d. Similarly, the specimens for shrinkage measurement at the age of 28 d were perfectly in sealed condition before the start of test.

![Fig. 2 Creep test: (a) specimens; and (b) loading frame](image)

3 Model selection

ACI-209(1992), B3 and CEB-FIP(90) models were considered in the preliminary phase of model selection. Comparison of the experimental data with the computed results found that the results computed by ACI-209(1992) and B3 agreed better than those by CEB-FIP(90) with the experimental data. Therefore, CEB-FIP (90) model was not used for further study. Model ACI defines creep as a function of slump, air content, s/a, curing condition, humidity and dimension. Considering different mixes can be prepared having the same above parameters which lead to the same creep coefficient despite having varied strength, w/c ratio, concrete grade, cement content and total aggregate content, ACI model has a serious drawback in its parameter selection. In contrast, B3 model defines creep as a function of concrete grade, cement content, w/c ratio, aggregate content, etc., which are major parameters to define concrete uniquely. Therefore in this study, we used B3 model and modified it through regression analysis with experimental data to include the effects of the type and amount of admixture and super-plasticizer on creep, which the original model neglects.

In B3 model, the total strain $\varepsilon(t)$ under a constant stress $\sigma$ applied at the age $t'$ is described as

$$\varepsilon(t) = J(t,t')\sigma + \varepsilon_{sh}(t) + \alpha \Delta T(t),$$

(1)

where $\Delta T(t)$ is the temperature change from the reference temperature at time $t$; $\alpha$ is the thermal expansion coefficient at the time when the loading starts; $t_0$ is the time when drying on the specimen begins; $\varepsilon_{sh}(t)$ is the shrinkage strain; and $J(t,t')$ is the compliance function defined as the strain (creep plus elastic) at the age $t'$ caused by the uniaxial stress $\sigma$, and is given by

$$J(t,t') = q_1 + C_q(t,t') + C_\delta(t,t',t_0),$$

(2)

where $q_1$ is the instantaneous strain; $C_q(t,t')$ is the compliance function for basic creep; and $C_\delta(t,t',t_0)$ is the additional compliance function due to simultaneous drying.

Finally, the creep coefficient $\phi(t,t')$, which represents the most convenient way to introduce creep into structural analysis, should be calculated from the compliance function. Thus, the creep coefficient $\phi(t,t')$ can be computed based on the compliance function and $E(t')$ modulus of elasticity at $t'$, i.e. $\phi(t,t') = E(t')J(t,t') - 1$.

4 Comparison of experimental and computed creep data for drying concrete

4.1 Total time dependent strain

Time dependent strain components (basic creep, drying creep and shrinkage) were calculated using B3 model for the types of concrete used, despite that it did not consider the effect of plasticizers and admixtures (additives). The total strain observed on specimens with sustained loading during a period of 700 d and the corresponding total strain from B3 model are shown in Fig. 3.
4.2 Shrinkage strain

Fig. 4 illustrates the comparison of shrinkage test results with those calculated by using B3 model. The discrepancies are smaller than those from creep measurement. Correction is still necessary, however.

5 Results analysis and discussion

From Fig. 3, it can be seen that the total strain of sealed concrete obtained from tests is distinctly lower than that calculated by B3 model; the trends of the lines are similar, though.

5.1 Adjustment for specimens loaded at 20% of ultimate capacity

The observed total strain includes $C_0(t,t')$, $C_d(t,t',t_0)$ and $\varepsilon_d(t)$. The temperature effect is already subtracted. Thus, the creep strain $C_0(t,t') + C_d(t,t',t_0)$ can be obtained by subtracting the shrinkage strain from the observed total strain. The experimental and model calculated results of $C_0(t,t') + C_d(t,t',t_0)$ for specimens loaded at 20% of ultimate capacity are shown in Fig. 5. Through regression analysis, a correction equation is developed.

For C40,

$$\{C_0(t,t')+C_d(t,t',t_0)\}_{\text{modified}} = 1.0386 \left[C_0(t,t')+C_d(t,t',t_0)\right] - 8.4654,$$

(3)

and for C50,

$$\{C_0(t,t')+C_d(t,t',t_0)\}_{\text{modified}} = 0.9866 \left[C_0(t,t')+C_d(t,t',t_0)\right] - 4.4966.$$

(4)

Thus, the modified compliance function will be the
sum of instantaneous strain and creep strain, i.e.,

$$J(t, t') = q_i + \left[ C_0(t, t') + C_d(t, t', t_0) \right]_{\text{modified}}.$$  \hspace{1cm} (5)

When the creep is assumed to be proportional to the applied stress, for an applied stress $\sigma$, the total strain is

$$\varepsilon(t) = J(t, t') \sigma + \varepsilon_d(t) + \alpha \Delta T(t).$$  \hspace{1cm} (6)

5.2 Adjustment for stress strength ratio

Creep strains observed for specimens loaded at the 20% stress level are compared with those at 40% and 60% load levels as shown in Fig. 6. The effect of stress level on creep is summarized in Table 3.

![Fig. 4](image4.png)

Fig. 4 Experimental and B3 model computed shrinkage strain over time $t$ for Specimens (a) C40-SH-18-D and C50-SH-18-D; and (b) C40-SH-28-D and C50-SH-28-D

![Fig. 5](image5.png)

Fig. 5 Correction equation for (a) C40 and (b) C50 types of concrete, where $C_0(t, t')$ is the basic creep and $C_d(t, t', t_0)$ is the additional creep due to simultaneous drying
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Table 3  Effect of stress level on creep

<table>
<thead>
<tr>
<th>$\sigma / \sigma_u$</th>
<th>$\varepsilon$</th>
<th>Sample size</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>10</td>
<td>0.500</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>40</td>
<td>2.053</td>
<td>90</td>
<td>0.086</td>
</tr>
<tr>
<td>60</td>
<td>3.100</td>
<td>24</td>
<td>0.068</td>
</tr>
</tbody>
</table>

Notes: $\sigma$ is the stress loaded on and $\sigma_u$ is the ultimate strength of a specimen; $\varepsilon$ is the ratio of the creep strain under a load to the creep strain when $\sigma / \sigma_u$ is 0.2, and is assumed to be linear with the stress up to $\sigma / \sigma_u$ is 0.2; and N/A means not applicable.

A polynomial equation of second degree could be fitted as shown in Fig. 7 which represents the ratio of the creep strain under a stress to that under the 20% stress level.

$$
\varepsilon(t) = J(t,t') \left[ 3 \times 10^{-5} \left( \frac{100\sigma}{\sigma_u} \right)^2 + 0.0498 \frac{100\sigma}{\sigma_u} \right] \times 
0.2\sigma_u + \varepsilon_{0u}(t) + \alpha \Delta T(t),
$$

(7)

where

$$
3 \times 10^{-5} \left( \frac{100\sigma}{\sigma_u} \right)^2 + 0.0498 \frac{100\sigma}{\sigma_u} \times 0.2\sigma_u
$$

is the correction for the stress level and is denoted by $K_{\sigma}$ hereinafter.

Fig. 6  Comparison of creep strain under a loading of 20% capacity $\varepsilon_{20}$ with that (a) under 40% capacity $\varepsilon_{40}$; and (b) under 60% capacity $\varepsilon_{60}$ over a time $t$ of 700 d

Fig. 7  Plot for effect of strength stress ratio, where $\sigma$ is the stress loaded on and $\sigma_u$ is the ultimate strength of a specimen; and $\varepsilon_{0u}$ is the ratio of the creep strain under a load to the creep strain when $\sigma / \sigma_u$ is 0.2

5.3 Comparison of tested shrinkage results with B3 model and adjustment of B3 model for shrinkage

There is noticeable discrepancy between experimental and calculated shrinkage data, though not as serious as in the case of creep. Shrinkage data observed and calculated using B3 model are compared in Fig. 8, and the adjustment for shrinkage calculation is as follows.

For C40,

$$
\varepsilon_{sh}(t)_{\text{modified}} = 0.762 \varepsilon_{sh}(t) - 11.741,
$$

(8)
and for C50,
\[ \varepsilon_{sh}(t)_{\text{modified}} = 0.972\varepsilon_{sh}(t) - 32.100. \] (9)

\[ y = 0.761x - 11.741 \]

\[ y = 0.9718x - 32.1 \]

**Fig. 8** Correction of shrinkage strain calculation for (a) C40 and (b) C50 concrete

### 5.4 Final adjusted B3 model

The final adjusted equation for total strain is

\[ \varepsilon(t) = J(t, t') \varepsilon + \varepsilon_{sh}(t)_{\text{modified}} + \alpha \Delta T(t). \] (10)

It should be notified that the adjustment was derived based on only C40 and C50 concrete, which may not be applicable for other concrete types.

### 6 Conclusions

Concrete is the most widely used structural material in the world. With the advancement in concrete technology a very contrasting mix proportion of additives compared with that several decades before has been used in the recent decade. A lot of research work has been done for understanding failure criteria and strength properties of modern concrete. However, in engineering design work, we have been using the same creep prediction model that was used several decades before, which merely accounts the admixture content. In this present research, we investigated the discrepancy in creep data obtained from experimental tests and those predicted by the B3 model, derived the modification terms for calculating the creep strain of C40 and C50 types of concrete, and concluded the following.

1) Creep properties of concrete with admixtures and super-plasticizers are different to those without additives.

2) The parameters in ACI-209(92) model may not describe well the creep of concrete.

3) Adjustment of B3 model is necessary for predicting creep strains in structures where concrete is used with additives.

4) There is not a linear relation between the stress level and the creep rate, instead a higher rate of creep is observed with higher stresses.

5) All available creep models leave the effects of super-plasticizers and admixtures out of consideration although these ingredients have been very essential constituents of concrete used in recent days. Introducing proper adjustment to available models will lead to better prediction of creep related deformation and stresses in structures.

6) Creep of concrete with varying dose and varying types of admixtures could be sequel of this research.

### References


