A Method to Improve the Concrete Shrinkage Prediction Based on Short-Time Tests

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Abstract. The computational accuracy of concrete prediction models is the key to investigate shrinkage influence on performance of concrete structure. Commonly used concrete prediction models are evaluated for their accuracy by comparing their predicted results against the six groups of test data that are collected from published papers. The results show that prediction models were not coincided very well with the experimental data. The phenomenon of concrete shrinkage is a result of several interacting physical mechanisms and is influenced by many variable factors. The shrinkage deformations invariably exhibit large statistical scatter. The calculated results of prediction models could not agree very well with the test results. In order to improve the calculation accuracy of concrete shrinkage prediction models, updating the prediction models based on short-time tests is an effective method. And the general method is not proper because of ill-posed problem. So a new improvement method was proposed and suggested in this study. Seven groups of concrete shrinkage test data are used to evaluate the suggested method. It could be found that the suggested method could match better with the test data.

1. Introduction
During the past few decades, the long-term deflection and cracks of long-span prestressed concrete bridge is getting more and more serious in terms of structure safety [1], many bridges have already been found to exhibit excessive long-time deflections which may lead to the collapse of bridges [2-6].

The time-dependent performance of concrete, governed by creep and shrinkage, is of particular importance. The concrete shrinkage and creep phenomenon has a double effect on prestressed concrete structures as it leads to both long-term deflection of bridge structure and prestress losses. Accuracy of shrinkage and creep prediction models is important in the design of concrete structures. A huge number of prediction models are available in practice, such as ACI 209 model recommended by the American Concrete Institute [7], CEB 90 model recommended by the Euro-international concrete committee [8], GL2000 model developed by Prof. Gardner in Canada [9], and the B3 model from Prof. Bazant at Northwestern University [10].

A fair amount of concrete prediction models were proposed, but there are still a number of problems needed further research. Various researchers have investigated the accuracy of these models for shrinkage and creep prediction and compared with the experimental data [8, 11-13]. But the results
show that prediction models were not coincided very well with the experimental data. In order to improve the calculation accuracy of concrete shrinkage prediction models, updating the prediction model based on short-time tests is an effective method \(^{10, 14-17}\). The method proposed by Prof. Bazant \(^{10}\) is effective to improve creep prediction model, and is widely acknowledged \(^{14, 16}\). Improving shrinkage prediction is more difficult. And the general method is not proper because of ill-posed problem \(^{10}\). So a new method was proposed and suggested in this study. Examples of improving shrinkage prediction model based on the short-time tests were also presented to verify the suggested method.

2. Evaluation of Concrete Shrinkage Prediction Models

In order to evaluate the accuracy of commonly used concrete prediction models, six groups of concrete shrinkage test data were collected from published papers \(^{18-20}\). Commonly used concrete prediction models include B3 prediction model \(^{10}\), JSCE1996 prediction model \(^{21}\), JSCE2002 prediction model \(^{21}\), GL2000 prediction model \(^{9}\), GZ 1993 prediction model \(^{12}\) and JTJ D62-2004 prediction model \(^{22}\). The predicted shrinkage values of prediction models are compared with the collected test datum, and the CEB Coefficient of Variation Method \(^{8}\) is used to determine the precision of these predicted values.

Results of the CEB coefficient of variation for shrinkage strain \(\omega_{\text{CEB}}\) are summarized in Table 1 (In the cause of data sets without complete experimental parameters needed by prediction models, the results are presented by “—” instead). It can be observed that their predicted shrinkage values were not coincided very well with experimental values. In all shrinkage prediction models, the average \(\omega_{\text{CEB}}\) is within the range of 6.1% and 190.7%. Meanwhile, a prediction model presents highly variable \(\omega_{\text{CEB}}\) in different data sets. For example, the \(\omega_{\text{CEB}}\) of JTJ D62-2004 prediction model is within the range of 17.4% and 81.7%.

| No | B3  | GL2000 | JTJD62 2004 | JSCE 2002 | JSCE 1996 | GZ1993 |
|----|-----|--------|-------------|-----------|-----------|--------|
| I  | 73.5| 31.7 | —           | 25.4      | 32.7      | 25.1   |
| II | —   | 82.9 | 17.4        | —         | —         | 62.8   |
| III| —   | 61.9 | 24.0        | —         | —         | 36.0   |
| IV | —   | 190.7| 81.7        | —         | —         | 116.4  |
| V  | 68.2| 34.5 | 70.4        | 17.6      | 6.1       | 35.0   |
| VI | 48.0| 22.1 | 65.2        | 37.1      | 44.6      | 22.5   |
| Average | 63.24 | 70.63 | 51.74 | 26.70 | 27.80 | 49.63 |

An accurate prediction model of concrete shrinkage is crucial for durability and long-time serviceability of concrete structure. But it is an extremely difficult problem, because the phenomenon is a result of several interacting physical mechanisms and is influenced by many variable factors such as mixture proportion, mechanical properties including strength and modulus of elasticity, ambient relative humidity, duration of drying, and duration of loading. And specimen size also has some influence on the shrinkage development of concrete. The largest source of uncertainty of shrinkage prediction model is from the dependence of model parameters stemming from the composition and strength of concrete. This uncertainty can be greatly reduced by improving prediction models based on short-time tests.
3. The Method of Improving the Concrete Shrinkage Prediction Based on Short-Time Tests

3.1 Problems in the General Method of Updating Shrinkage Prediction Models by Using Short-Time Tests

The performance of creep and shrinkage prediction models can be increased by carrying out short-time measurements on the given concrete and adjusting the values of empirical parameters in prediction models accordingly. The general method of updating creep and shrinkage prediction models can be explained by taking B3 prediction model as an example.[10]

As for updating the creep prediction model, according to the B3 prediction model, the creep could be calculated by Eq. 1:

\[
J(t,t') = q_1 + C_c(t,t') + C_d(t,t')
\]

in which the creep compliance function \(J(t,t')\) is strain (creep plus elastic) at time \(t\) caused by a unit uniaxial constant stress applied at age \(t'\), \(q_1\) = instantaneous strain due to unit stress, \(C_c(t,t')\) is creep compliance function for basic creep, and \(C_d(t,t')\) is additional creep compliance function due to simultaneous drying. These parameters and expression were described in details by Bazant in his paper[10]. The updated creep compliance function can be described in Eq. 2:

\[
J(t,t') = p_1q_1 + p_2(C_c(t,t') + C_d(t,t',t_b))
\]

in which \(p_1\) and \(p_2\) were two updated parameters which play the role of updating empirical constitutive parameters, the values of which could be obtained by least-square regression based on tests.

As far as updating the shrinkage prediction model is concerned, according to the B3 prediction model, values of the shrinkage strain should be calculated by Eq. 3:

\[
\varepsilon_{sh}(t,\tau) = \varepsilon_{s,\infty} \frac{E(607)}{E(\tau + \tau_{sh})} k_h \tan[h[(t-\tau)/\tau_{sh}]]^{1/2}
\]

in which \(\varepsilon_{sh}(t,\tau)\) is the concrete shrinkage strain at time \(t\), \(\tau\) is the age of concrete drying commenced, \(\varepsilon_{s,\infty}\), \(k_h\), \(\tau_{sh}\), \(E(607)\), and \(E(\tau + \tau_{sh})\) constants depend on concrete component, test environment, and etc., which are not related to the shrinkage duration. \(E(607)\) = modulus of elasticity at 607 days, while \(E(\tau + \tau_{sh})\) = modulus of elasticity at time \(\tau + \tau_{sh}\). \(\tan[h[(t-\tau)/\tau_{sh}]]^{1/2}\) is the equation to describe the development of shrinkage with time.

The updated shrinkage prediction model could be usually expressed as in Eq. 4:

\[
\varepsilon_{sh}(t,\tau) = p_1\varepsilon_{s,\infty} \frac{E(607)}{E(\tau + \tau_{sh})} k_h \tan[h[(t-\tau)/p_2\tau_{sh}]]^{1/2}
\]

in which \(p_1\) and \(p_2\) were used to update empirical constitutive parameters based on tests.

If \(k(k>2)\) data points are obtained by carrying out short-time tests, therefore \(t_i\) and \(\varepsilon_{sh}(t_i,\tau)\) are known (for \(i=1, 2,\ldots k\)).

\[
\varepsilon_{sh}(t_i,\tau) = p_1\varepsilon_{s,\infty} \frac{E(607)}{E(\tau + \tau_{sh})} k_h \tan[h[(t_i-\tau)/p_2\tau_{sh}]]^{1/2}(i = 1,2,\ldots k)
\]

Eq. 5 includes equalities, but only \(p_1\) and \(p_2\) is unknown quantity. And the values of them can be obtained by regression.
Hyperbolic tangent function or Ross’ hyperbola function \[ \tanh\left(\frac{(t - \tau)}{F}\right) \] is used to describe the development of shrinkage with time in usual shrinkage prediction models, which cause an ill-posed problem in general methods of updating shrinkage prediction models \[10\]. The problem can be explained by taking B3 prediction model as an example. The updated B3 shrinkage prediction model can be written as Eq. 2, and it can be simplified as in Eq. 6:

\[ \varepsilon_a(t, \tau) = E \cdot \tanh\left(\frac{(t - \tau)}{F}\right)^{1/2} \]  

(6)

in which \(E\) and \(F\) are constants which are not related to the shrinkage duration depending on concrete component, test environment, and etc.. Figure 1 shows that different values of parameters \(E\) and \(F\) fits well with the short-time data. If only short-time data are known, different shrinkage curves according to Eq. 6, corresponding to very different parameter values, can accord with these short-time data points for a long period of time. In other words, if the data points beyond reach the time at which the two curves shown in Figure 1 beg into significantly diverge, there is no way to determine the parameters \(E\) and \(F\) unambiguously. According to the mentioned phenomenon above, improved prediction model based on short-time tests accords with initial test results quite well, as shown in Figure 2, but the curve may beg into significantly diverge from tests after a period of time. \(\) (This is true not only for the formulae of B3 prediction model but also for all other shrinkage formulae, including the Ross’ hyperbola used in ACI209-92 prediction model \[10\].)

3.2 A New Method to Improve Shrinkage Prediction Based on Short-time Tests

According to Eq. 2, adjusting the values of the empirical parameters in prediction model is an effective method to improve creep prediction model. The method was proposed by Bazant \[10\] and was widely recommended\[14, 16\].
Improving shrinkage prediction is quite difficult. The general method described in Eq. 4 and Eq. 5 is not suitable for predicting the shrinkage because of the ill-posed problem analyzed before. So a new method is needed to be proposed to improve the shrinkage prediction model. In this paper, the suggested method includes two phases. The shrinkage duration less than 50 days is phase I, and the updated shrinkage prediction model can be described in Eq. 4. Shrinkage duration exceeding 50 days is phase II. Calculation and analysis of general prediction models indicate that the development of concrete shrinkage with time is similar to concrete creep while shrinkage duration exceeds 50 days. So the formula of creep prediction model can be used to improve shrinkage prediction in phase II. Shrinkage duration of short-time tests should be over 50 days, and at least two data points of tests should be used in phase II.

3.2.1 Comparing the Temporal Development of Concrete Shrinkage and Creep

In order to compare the temporal development of concrete shrinkage and creep, ratio of shrinkage strain to creep coefficient can be defined by Eq. 7, the age of concrete drying commenced is the same as the age at loading on concrete:

\[ k(t-\tau) = \varepsilon_{sh}(t,\tau) / \varphi(t,\tau) \]  

(7)

in which, \( \varepsilon_{sh}(t,\tau) \) is the shrinkage strain at time \( t \), \( \tau \) is the age of concrete drying commenced, and \( \varphi(t,\tau) \) is the creep coefficient at time \( t \) caused by the stress applied at age \( \tau \). The development of \( k(t-\tau) \) with time \( t-\tau \) can be obtained according to general prediction models.

According to ACI209-92 prediction model \([14]\), \( k(t-\tau) \) is calculated by Eq. 8.

\[ k(t-\tau) = \frac{\varepsilon_{sh}(t,\tau)}{\varphi(t,\tau)} = \frac{780 \times 10^{-6} \gamma_{sh}}{2.35 \gamma_{c}} \left( \frac{t-\tau}{35 + t-\tau} \right) \left( \frac{(t-\tau)\gamma_{c}}{10 + (t-\tau)\gamma_{c}} \right)^4 \]  

(8)

in which \( \gamma_{sh} \) and \( \gamma_{c} \) are empirical constitutive parameters which are not related to the time, \( k(t-\tau) \) can be described in Eq.9 while \( f_i(t-\tau) \) plotted with respect to time is shown in Figure 3.

\[ f_i(t-\tau) = \left( \frac{t-\tau}{35 + t-\tau} \right) \left( \frac{(t-\tau)^{\gamma_{c}}}{10 + (t-\tau)^{\gamma_{c}}} \right) \]  

(9)

When \( t-\tau \) is within the range of 50 to 1000 days, the average value of \( f_i(t-\tau) \) is 1.161, the maximal value of \( f_i(t-\tau) \) is 1.212, the ratio of average value of \( f_i(1000) \) is 103.8%, and the ratio of maximal value of \( f_i(1000) \) is 108.3%. The values of \( f_i(t-\tau) \) change greatly when the time \( t-\tau \) is less than 50 days, but show little change and can be approximately a constant when \( t-\tau \) exceeds 50 days.

Similar conclusions can be obtained according to JSCE1996 prediction model \([21]\) and the prediction model proposed in 1986 by China Academy of Building Research (CABR 1986 prediction model) \([23]\).
According to CABR 1986 prediction model, \( k(t-\tau) \) is calculated by Eq. 10, and the time-dependent group of \( k(t-\tau) \) can be described as in Eq. 11:

\[
k(t-\tau) = A \frac{t-\tau}{152.79 + 3.27 \cdot (t-\tau)} \cdot \frac{(t-\tau)^{0.6}}{4.168 + 0.312 \cdot (t-\tau)^{0.6}}
\]

(10)

\[
f_s(t-\tau) = \frac{t-\tau}{152.79 + 3.27 \cdot (t-\tau)} \cdot \frac{(t-\tau)^{0.6}}{4.168 + 0.312 \cdot (t-\tau)^{0.6}}
\]

(11)

where \( \lambda \) is empirical constant which is unrelated to time.

According to JSCE1996 prediction model, creep strain per unit stress \( C_{cr}(t, \tau) \) can be estimated using Eq. 12, and the creep coefficient \( \varphi(t, \tau) \), which represents the most convenient way to introduce creep into structural analysis, should be calculated from Eq. 13. \( k(t-\tau) \) can be calculated by Eq. 14, and the time-dependent group of \( k(t-\tau) \) can be described in Eq. 15.

\[
C_{cr}(t, \tau) = \{1 - \exp[-0.09(t-\tau)^{0.6}]\} \cdot \varepsilon_{cr}'
\]

(12)

\[
\varphi(t, \tau) = E(\tau) \cdot C_{cr}(t, \tau)
\]

(13)

\[
k(t-\tau) = \varepsilon_{sh}(t, \tau) / \varphi(t, \tau) = \frac{\varepsilon_{sh}'}{1 - \exp[-0.108(t-\tau)^{0.6}]} \cdot \frac{1 - \exp[-0.09(t-\tau)^{0.6}]}{1 - \exp[-0.09(t-\tau)^{0.6}]}
\]

(14)

\[
f_s(t-\tau) = \frac{1 - \exp[-0.108(t-\tau)^{0.6}]}{1 - \exp[-0.09(t-\tau)^{0.6}]}
\]

(15)

in which \( \varepsilon_{cr}' \) and \( \varepsilon_{sh}' \) are empirical constants which are not time-varying parameters, \( E(\tau) \) is modulus of elasticity at loading age \( \tau \).

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**Figure 4. The values of \( f_s(t-\tau) \)**

**Figure 5. The values of \( f_s(t-\tau) \)**
The values of $f_i(t - \tau)$ (for $i = 1..3$) are summarized in Table 2, $f_2(t - \tau)$ and $f_3(t - \tau)$ plotted with respect to time are shown in Figure 4 and Figure 5 respectively.

| Prediction models | $f_1(t - \tau)$ | $f_2(t - \tau)$ | $f_3(t - \tau)$ |
|-------------------|-----------------|-----------------|-----------------|
| ACI 1992          | 1.212           | 0.121           | 1.016           |
| CABR 1986         | 1.161           | 0.115           | 0.995           |
| JSCE 1996         | 1.119           | 0.111           | 0.998           |

According to the three general prediction models, the values of $f_i(t - \tau)$ for $i = 1..3$ and $k(t - \tau)$ change greatly when the time $t - \tau$ is less than 50 days, but show little change and can be approximately a constant when $t - \tau$ exceeds 50 days. Therefore $k(t - \tau)$ is approximately equal to $k(1000)$. The phenomenon can be described as in Eq. 16.

$$k_{sv} = \frac{\varepsilon_{sh}(t, \tau)}{\psi(t, \tau)} = k(1000) \quad (\text{when} \ t - \tau \geq 50 \text{ days}) \quad (16)$$

3.2.2 The phase I of improving shrinkage prediction

In phase I, concrete shrinkage prediction model can be easily revised by short-time tests. The updated shrinkage prediction model can be described as in Eq. 4. In this function, $p_1$ and $p_2$ are material constants, which could be acquired by regression. The results of revised shrinkage prediction model can be evaluated and updated according to tests.

3.2.3 The phase II of improving shrinkage prediction

Eq. 17 and Eq. 18 are workable according to Eq. 16, $k_{sv}$ can be calculated as in Eq. 19, and $\Delta_{sv,50}$ can be expressed by Eq. 20 (when $t - \tau \geq 50$ days in phase II):

$$k_{sv} = \frac{\varepsilon_{sh}(t, \tau) - \varepsilon_{sh}(50 + \tau, \tau)}{\psi(t, \tau) - \psi(50 + \tau, \tau)} \quad (17)$$

$$\varepsilon_{sh}(t, \tau) = k_{sv}\psi(t, \tau) + \Delta_{sv,50} \quad (18)$$

$$k_{sv} = k(1000) = \frac{\varepsilon_{sh}(1000 + \tau, \tau)}{\psi(1000 + \tau, \tau)} \quad (19)$$

$$\Delta_{sv,50} = \varepsilon_{sh}(50 + \tau, \tau) - k_{sv}\psi(50 + \tau, \tau) \quad (20)$$

$\varepsilon_{sh}(1000 + \tau, \tau)$, $\psi(1000 + \tau, \tau)$, $\varepsilon_{sh}(50 + \tau, \tau)$, and $\psi(50 + \tau, \tau)$ can be calculated according to B3 prediction model. So $\Delta_{sv,50}$ is constant and independent of time. The creep coefficient $\psi(t, \tau)$ could be calculated easily from the creep compliance function $J(t, \tau)$ which was used by B3 prediction model:

$$\psi(t, \tau) = E(\tau)J(t, \tau) - 1 \quad (21)$$

According to Eq. 1, Eq. 18, and Eq. 21, $\varepsilon_{sh}(t, \tau)$ can be calculated by Eq. 22, $k_{sv}$ can be expressed by Eq. 23, and $\Delta_{sv,2}$ can be expressed by Eq. 24.

$$\varepsilon_{sh}(t, \tau) = k_{sv}J(t, \tau) + \Delta_{sv,1} \quad (22)$$

$$k_{sv} = k_{sv}E(\tau) \quad (23)$$
The updated shrinkage prediction can be rewritten as Eq. 25.

\[
\Delta_{\text{sh}2} = \Delta_{\text{sh},50} - k_{\text{sh}1}
\]  

(24)

In eq. 25, \(p_1\) and \(p_2\) are two updated empirical constitutive parameters \((k>2)\) could be obtained by the short-time tests, so \(\epsilon_{\text{sh}}(t_i, \tau)\) are known (for \(i=1, 2, \ldots, k\)).

\[
\epsilon_{\text{sh}}(t_i, \tau) = k_i \{p_1 q_i + p_2 [C_\text{s}(t_i, \tau) + C_\text{d}(t_i, \tau)]\} + \Delta_{\text{sh}2}
\]  

(25)

Eq. 26 includes equalities, only \(p_1\) and \(p_2\) is unknown quantity, and the values of them can be obtained by regression.

4. Evaluation of predicted Concrete Shrinkage Model based on the Short-time Tests

| No | Specimen Size(mm) | Concrete Strength Grade | Concrete Cubic Specimen 28-day Strength(MPa) | Water-to-Cement Ratio | Age at Drying (d) | Temperature (℃) | Relative Humidity (%) |
|----|-------------------|------------------------|---------------------------------------------|----------------------|------------------|----------------|----------------------|
| 1  | 150×150×450       | C50                    | 54.3                                        | 0.35                 | 7                | 20             | 50                   |
| 2  | 100×100×400       | C50                    | 56.1                                        | 0.39                 | 28               | 25             | 60                   |
| 3  | 100×100×400       | C50                    | 56.1                                        | 0.39                 | 28               | 25             | 60                   |
| 4  | 100×100×515       | C50                    | 61.3                                        | 0.43                 | 2                | 20             | 65                   |
| 5  | 100×100×515       | C50                    | 61.3                                        | 0.43                 | 7                | 20             | 65                   |
| 6  | 100×100×515       | C60                    | 70.2                                        | 0.35                 | 2                | 20             | 65                   |
| 7  | 100×100×515       | C60                    | 70.2                                        | 0.35                 | 7                | 20             | 65                   |

Seven groups of concrete shrinkage test data were used to illustrate the procedure of improving the concrete shrinkage prediction model and check the validity of the method. The main test parameters are summarized in Table 3. Results of test 1 shown in Figure 6 was collected from Nanjing Hydraulic Research Institute, and other six groups of test data (test 2 to 7) were collected from technical papers published in China [20, 24].

Figure 6. An example of improving the concrete shrinkage prediction model based on short-time test data

| No | B3 Model | The Revised B3 Model | The Suggested Method |
|----|----------|----------------------|----------------------|
| 1  | 66.6     | 14.1                 | 0.9                  |
| 2  | 374.3    | 50.2                 | 48.5                 |
As shown in Figure 6, the revised B3 model can be obtained by updating empirical parameters of B3 shrinkage prediction model according to Eq. 5. If the first 12 data points for the first 2 months of shrinkage duration are used in updating models, the suggested method which has the best performance. The calculated results of improved models including the revised B3 model and the suggested method agree better with the test results than B3 prediction model.

The CEB coefficient of variation (\(\omega_{CEB}\)) method is used to evaluate the accuracy of prediction models, including B3 creep prediction model, the revised B3 model, and the suggested method. Results are listed in Table 4, which indicates that improving shrinkage prediction model by the use of short-time tests is an effective way to improve the accuracy of concrete prediction models. The CEB coefficient of variation of improved models is far less than B3 prediction model. The suggested method has the least \(\omega_{CEB}\) in all groups of concrete shrinkage test data.

5. Conclusions
(1) Comparing the results of predicted shrinkage values of commonly used concrete prediction models with the test data, it could be found that the predicted shrinkage values were not coincided very well with experimental data.

(2) An accurate prediction model of concrete shrinkage is of crucial importance for durability and long-time serviceability of concrete structure. But it would be difficult to formulate without short-time tests, because of the effects of the great variety of additives and different combinations used on the model parameters.

(3) Seven groups of concrete shrinkage test data were used to evaluate the suggested method. It could be found that the suggested method could match better with the test data.

(4) Updating the prediction model based on short-time tests is an effective method to improve the calculation accuracy of concrete prediction models, which is thus worthy of further promotion and exploration.

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