Re-evaluation of CEB-FIP 90 prediction models for creep and shrinkage with experimental database

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Highlights

- An experimental database of creep and shrinkage of concrete is compiled.
- CEB-FIP90 prediction models for creep and shrinkage are re-evaluated using the database.
- Modified models for creep and shrinkage are present.

Graphical Abstract

Distribution of $f_{cu}$ of shrinkage database

Shrinkage strain residuals for CEB-FIP90 model versus time

Abstract

This paper aims to evaluate the CEB-FIP 90 model, which is commonly utilised to predict the creep and shrinkage effects of concrete structures, by comparing it with an extensive compiled database which combines the available data in literature and newly collected data from China. This database considers only concrete specimens with an average 28-day compressive strength between 30 MPa and 80 MPa, and restricts the relative humidity of the experimental environment to a maximum value of 95%. Three statistical methods are applied to evaluate the CEB-FIP 90 model: the residual method, the B3 coefficient of variation method, and the CEB coefficient of variation method. Based on the statistical regression analysis of the shrinkage and creep test data, the CEB-FIP 90 model is revised by modifying the influencing coefficients of the compressive strength of concrete and the time development functions of creep and shrinkage. The modified model is then subjected to evaluation and verification using the residual method, B3 coefficient of variation method and CEB coefficient of variation method. Based on verification with experimental data and corroboration with statistical analysis, the modified model performs better than CEB-FIP 90 model, especially with regards to high strength concrete.

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1. Introduction

Creep and shrinkage of concrete are volume changes that develop over time, leading to the development of stresses, cracking and excessive deflections which compromise the long term serviceability and durability of concrete structures. Thus, it represents a key consideration in design, especially for the design of long-span prestressed concrete structures. This paper presents an evaluation of the existing CEB-FIP 90 model and aims to propose some improvements to increase the applicability and accuracy of its predictions. Creep and shrinkage are complex mechanisms involving a multitude of often interrelated factors, and there has been no theory as of yet that is able to satisfactorily explain the...
entire phenomenon. As such, experimental studies have served as the basis for creep and shrinkage models, and current models are largely based on empirical data and observations. Since the early 20th century, extensive experimental research has been conducted that has led to a variety of prediction models for creep and shrinkage. These models can be divided into three types. The first type of model describes the overall development of creep and includes CEB-FIP 90 [1], ACI 209-82 [2], AASHTO [3], CZ [4], and GL 2000 [5]; the second type of model divides creep into basic creep and drying creep, and includes BP-KX, BP-2, and B3 [6]; and the last type of model separates recovery creep from unrecoverable creep, such as CEB-FIP 78 [7].

However, recent years have seen the increased application of high strength concrete in concrete structures. Due to the dense microstructure of high strength concrete, its creep and shrinkage behaviour is markedly different from normal strength concrete. Most of the existing prediction models for creep and shrinkage are derived from the statistical regression analysis of test data, and data on normal-strength concrete account for a significant proportion of the available test data. As a result, the applicability of the existing prediction models to high strength concrete needs to be further evaluated, and there is also a need to generate a modified model based upon a new database incorporating more data on high strength concrete for use in engineering practice.

Currently, the widely adopted model for creep and shrinkage is the CEB-FIP 90 Model [1], which has been adopted in numerous concrete codes across the world such as the JTG D62-2004 [8]. Therefore this paper focuses on the evaluation of CEB-FIP 90 model, given its extensive application around the world.

The CEB-FIP 90 model is valid for concrete that has an average 28-day compressive strength in the range of 20 MPa to 90 MPa and an environmental relative humidity in the range of 40–100%, at a mean temperature of 5–30°C. The minimum compressive strength of concrete was set at 33 MPa in the compiled creep and shrinkage database for two reasons. First, the proportion of low-strength concrete will affect the applicability of the statistical regression model to high strength concrete; thus, a limited amount of extremely low-strength concrete was included in the database. Second, the creep and shrinkage of concrete play an important role in determining the long-term behaviours of long-span concrete structures, which are typically constructed with prestressed concrete. As specified in AASHTO [3], the compressive strength for prestressed concrete should not be lower than 28 MPa. In practice, however, the specified compressive strength for prestressed concrete usually exceeds 30 MPa. Therefore, a statistical evaluation of the CEB-FIP 90 model for concrete that has a compressive strength exceeding 30 MPa is imperative.

In comparison to previously established databases, such as those constructed by Bazant et al. [9,10] and Al-Manaseer and Lam [11], the present database is governed by three key distinguishing factors. First, the minimum compressive strength of concrete is limited to 33 MPa while other databases include numerous specimens with compressive strengths lower than 30 MPa. Second, experiments conducted in environments with 95% or 100% relative humidity are not considered, because these relative humidities only occur underwater. The range of environmental relative humidities considered in the database does not exceed 95%, which is the general maximum value for atmospheric humidity. Third, many experiments that were conducted in China were added to the database.

The compiled database is utilised to re-evaluate the CEB-FIP 90 model by the residual method, the B3 coefficient of variation method [12] and the CEB coefficient of variation method [13]. Furthermore, modified prediction models for creep and shrinkage that are based on the statistical regression analysis of the database are presented. The results of the statistical evaluation can provide the basic parameters for the uncertainty analysis of the effects of creep and shrinkage in concrete structures [14].

2. Experimental databases of creep and shrinkage

2.1. Experimental database of shrinkage

In total, 206 groups of specimens which were subjected to shrinkage tests were chosen for incorporation in the database, of which 48 groups were tested in China; this gives a total of 2838 data points [10,15–22]. The distributions of the major parameters, namely the measured mean 28-day compressive strength of concrete, f\text{cm}; the environmental relative humidity, RH; and the effective thickness which accounts for the volume/surface ratio, h, are shown in Fig. 1. It can be seen from Fig. 1 that 26.2% of the shrinkage specimens had a mean 28-day compressive strength in the range of 60–81 MPa, while the majority of concrete specimens had a mean compressive strength in the range of 30–60 MPa. In practice, the compressive strength of concrete that is widely used in prestressed concrete structures falls within the same strength range; hence, to some extent, the established database is representative of the shrinkage tendency of commonly used concrete. In this database, 91.7% of the shrinkage experiments were performed in an environment with relative humidity within the range of 40–80%, which is similar to the environmental conditions of actual concrete structures. Because the shrinkage experiments were performed under standard indoor environmental conditions, the effective thickness of the specimen was smaller than the thickness of the actual concrete member. 93.7% of the specimens had an effective thickness in the range of 25 mm to 100 mm.

2.2. Experimental database of creep

In total, 179 groups of specimens originally devoted to creep tests (35 groups were conducted in China) have been selected to give a total of 3598 data points [10,15,18,19,23–25]. The distributions of the major parameters, namely f\text{cm}, RH, h, and \( r \) are shown in Fig. 2. \( r \) represents the concrete age at loading. It can be observed from Fig. 2 that 86.0% of the creep specimens had a mean 28-day compressive strength between 30 MPa and 60 MPa. In practice, the compressive strength of concrete that is widely used in prestressed concrete structures falls within the same strength range; hence, to some extent, the established database is representative of the creep tendency of commonly used concrete. In this database, the majority of the environmental relative humidities lie between 50% and 65%, which is similar to the actual construction environment. Similar to the shrinkage experiments, the creep experiments are carried out in a standard indoor environment, and the effective thickness of the specimen is smaller than the thickness of the actual concrete member. 93.9% of the specimens had an effective thickness in the range of 25–100 mm. In the database, the loading ages of creep specimens range from 5 days to 28 days, which accounted for 69.3% of the total specimens. For prestressed concrete bridges, the concrete age at loading generally exceeds 3 days; however, for long-span prestressed concrete bridges that are built via the cantilever construction method, the concrete age at loading ranges from 5 days to hundreds of days. The various stages of construction for long-span concrete bridges, such as post-tensioning, casting segments of bridge in-place, stretching the closure tendons, and deck paving, all utilise concrete with different loading ages. Hence, the database incorporated creep specimens with loading ages greater than 28 days (21.1% of the data).

3. Re-evaluation of the CEB-FIP 90 Model

The CEB-FIP 90 creep and shrinkage models are evaluated by using the aforementioned database. The predicted creep compliance (also known as creep function, which is the sum of the instantaneous elastic strain and the creep strain under unit uniaxial constant stress) and shrinkage strains in the model are compared with the test data that were extracted from the database. Three types of evaluation methods, the residual method (RV), the B3 coefficient of variation (\( \nu_{B3} \)), and the CEB coefficient of variation (\( \nu_{CEB} \)) were applied to evaluate the prediction accuracy of the CEB-FIP 90 model.

When compared against the B3 coefficient of variation method and the CEB coefficient of variation method, the residual method appears relatively simple. The main underlying principle of the residual method is the subtraction of the predicted values from the measured values, followed by the analysis of the magnitude and distribution of the discrepancy. A positive difference implies that the model overestimated the shrinkage strain or creep compliance values. On the other hand, underestimation of the