Investigation of the Significance of Factors Affecting Long-Term Creep of Concrete using Screening Designs

H Daou¹ and W Raphael¹

¹ Saint-Joseph University, Beirut, Lebanon

Email: hikmat.daou@net.usj.edu.lb

Abstract. Creep has a main role in predicting delayed strain in concrete members and in estimating losses in prestressed concrete, such as nuclear containment vessels, bridges girders, etc. For that, the interest in studying creep has grown significantly. This study aims to investigate the significance of different factors affecting creep of concrete using the Northwestern University (NU) creep database. Experiments have been carried out at different conditions of water-cement ratio (w/c), aggregate-cement ratio (a/c), cement content (c), cement type (R or RS), admixtures, mean compressive strength (f_cm), volume-surface ratio (v/s), relative humidity (RH), age at loading (t_0) and stress level (sigma). In order to determine the significance of these factors, three statistical methods have been used: Daniel Plot, Lenth Plot and Bayesian screening. The results of this analysis can be used to build accurate computational models to predict creep of concrete by considering the major effects identified.

1. Introduction

Concrete is known by its time-dependent volume changes where it shrinks during drying and creeps under sustained stresses. These changes in volume lead to an excessive long-term deflection of the structural members, loss of prestressing force in prestressed concrete elements, wide cracks in the tension members and redistribution of stresses with time in composite concrete structures. Therefore, designers and engineers must accurately predict creep and shrinkage strains in their structural analysis. Creep strain represents the time-dependent increase in strain under sustained constant load taking place after the initial strain at loading. The creep strain may be several times greater than the initial strain. Creep strain may be subdivided into a drying and a non-drying component, termed drying and basic creep, respectively. Basic creep represents the creep at constant moisture content with no moisture movement through the material, and is consequently independent of the specimen size and shape. It has not been determined whether basic creep approaches a final value, even after 30 years of measurement of sealed specimens [1, 2]. Drying creep is the additional creep occurring in a specimen exposed to the environment and allowed to dry. As it is caused by the drying process, drying creep depends on the size and shape of the specimen and may be expected to show a limiting value at long term [3, 4].

Creep mechanism is a complex process that is affected by significant number of parameters. For this purpose, it is crucial to know these parameters affecting creep of concrete. Many studies found in literature study the factors affecting the creep of concrete: quantity of aggregate [5], properties of aggregate [6], water content, cement content [7], air content [8], type of cement [9], relative humidity [10], temperature [11, 12], load [13], curing [14], size and shape of members [15] and loading age [16]. The creep of concrete is also affected by the admixtures: for example, the concrete containing silica fume exhibits a lower creep than the controlled (no silica fume) specimen under drying conditions.
while it showed a 12% higher creep than the controlled specimen under sealed conditions [17]. Moreover, Mazloom et al. [18] show that the creep strain decreased with increase in silica fume. Some studies of the effect of the fly ash show that the increase in fly ash content increases creep [19, 20] whereas other studies conclude that the increase in fly ash content decreases the creep [21, 22]. Other authors studied the effects of self-compacted concrete mixes containing mineral admixtures [23 - 25].

The prediction of creep strain in concrete structures is important to assess its serviceability and durability conditions. Many models for predicting creep are proposed for both normal and high strength concrete [26-33]. The model recommended by ACI Committee 209 found in ACI 209R-92 [34] to predict creep requires age of concrete when drying starts, age of concrete at loading, curing method, relative humidity, volume-surface ratio and cement type. The Bazant-Baweja B3 model [35] clearly separates basic and drying creep and considers the following factors to predict creep: age of concrete when drying starts, age of concrete at loading, aggregate content, cement type, mean concrete compressive strength at 28 days, curing method, relative humidity, shape of specimen, volume-surface ratio and water content in cement. CEB MC90-99 model [36] presents the prediction model of shrinkage and creep in concrete for both normal and high-strength concrete. This model requires age of concrete when drying starts, age of concrete at loading, mean concrete compressive strength at 28 days, relative humidity, volume-surface ratio and cement type. The GL2000 model [37] is also a model used to predict shrinkage and creep in concrete requiring age of concrete when drying starts, age of concrete at loading, relative humidity, volume-surface ratio, cement type and mean concrete compressive strength at 28 days. The factors required in creep model prediction should be the most factors affecting creep of concrete. The previous studies investigate the factors affecting creep of concrete by changing one factor and keeping all other factors as constant. Therefore, the weight of effect or the significance of factor cannot be assessed.

This study aims to investigate the significance of ten factors affecting the creep of concrete: water-cement ratio, aggregate-cement ratio, cement content, mean concrete compressive strength, effective thickness, age at loading, relative humidity, sustained stress, type of cement, and presence of admixtures. The NU database is used and the analysis is carried out using different methods of screening designs: Daniel Plot, Lenth’s Plot and Bayesian screening. The results can be used to build accurate computational models to predict creep of concrete by considering the major effects identified in this analysis.

2. Experimental database
This study used the latest database assembled at Northwestern University (NU) during 2010-2013 under the support of the U.S. Department of Transportation [38]. This database is constituted of approximately 1433 creep tests, of which approximately 800 creep curves contain admixtures. The tests in this database were performed using different parameters and under various conditions. For each test, the mix proportions, testing conditions, specimen geometries and admixtures are documented and the following parameters are provided: water-cement ratio, aggregate-cement ratio, cement type, mean concrete compressive strength, effective thickness, age at loading, temperature, relative humidity, sustained stress, and admixtures type and percentage.

This study aims to study the significance of factors affecting long-term creep; therefore the data used was limited for creep compliance at 3000 days and ten factors were considered as independent variable: water-cement ratio ($w/c$), aggregate-cement ratio ($a/c$), cement content (c in kg/m³), mean concrete compressive strength ($f_{cm}$ in MPa), effective thickness ($v/s$ in mm), age at loading ($t_0$ in days), relative humidity (RH in %), sustained stress (sigma in MPa), type of cement (R or RS) and presence of admixtures. In order to conduct screening designs, the data used in this study was organized and converted to a two-level factorial design as shown in Table 1.
3. Methodology

Table 1. Division criteria of data.

| Factor          | -1       | +1       |
|-----------------|----------|----------|
| w/c             | < 0.5    | ≥ 0.5    |
| a/c             | < 5      | ≥ 5      |
| c               | < 350    | ≥ 350    |
| f/cm            | < 50     | ≥ 50     |
| t₀              | < 28     | ≥ 28     |
| RH              | < 55     | ≥ 55     |
| v/s             | < 30     | ≥ 30     |
| Sigma/f_c      | < 0.3    | ≥ 0.3    |
| Type of cement  | R        | RS       |
| Existence of admixture | no | yes |

In order to study the significance of the factors affecting long-term creep of concrete, the concrete compliance function \( J(t,t₀) \), defined using Equation (1), was unified for \( t=3000 \) days.

\[
J(t, t₀) = \frac{1}{\sigma(t₀)} [\varepsilon_{el}(t₀) + \varepsilon_{cr}(t, t₀)]
\]  

where \( \sigma(t₀) \) is the sustained stress, \( \varepsilon_{el}(t₀) \) is the instantaneous elastic strain, and \( \varepsilon_{cr}(t,t₀) \) is the creep strain between \( t \), time of evaluating creep, and \( t₀ \), time of load application.

In the NU database, there are many tests where readings were stopped after a period of loading that is less than 3000 days while other tests have readings that exceed 3000 days with no reading at this time. For that, extrapolation (see Equation (2)) and interpolation (see Equation (3)) were applied to calculate \( J_{exp}(3000,t₀) \) using the compliance \( J_{EC2} \) calculated using the equation of the Eurocode 2 [39].

\[
J_{exp}(3000, t₀) = J_{exp}(t₁, t₀) + [J_{EC2}(3000, t₀) - J_{EC2}(t₁, t₀)]
\]  

\[
J_{exp}(3000, t₀) = J_{exp}(t₁, t₀) + [J_{EC2}(3000, t₀) - J_{EC2}(t₁, t₀)] \times \frac{J_{exp}(t₂, t₀) - J_{exp}(t₁, t₀)}{J_{EC2}(t₂, t₀) - J_{EC2}(t₁, t₀)}
\]

where \( J_{exp}(t₁,t₀) \) and \( J_{exp}(t₂,t₀) \) are the results of the compliance at time \( t₁ \) and \( t₂ \), respectively with \( t₁ \) days < 3000 days < \( t₂ \) days; \( J_{EC2}(t₁,t₀) \), \( J_{EC2}(3000,t₀) \) and \( J_{EC2}(t₂,t₀) \) are the compliance predicted by Eurocode 2 at time \( t₁ \), 3000 and \( t₂ \) days, respectively.

In screening experiments, factor sparsity is usually assumed. It means only a few of all factors considered in the experiment will actually affect the response. The statistical methods used in this study are: Daniel Plot, Lenth’s Plot and Bayesian screening.

3.1. Daniel plots

Daniel Plots, which is also known as normal plot of effects, arrange the estimated factors effects in a normal probability plot [40]. The factors “out of the straight line” are identified as potentially active factors. It is an important, commonly used and successfully employed tool for identifying important factors in 2-level full and fractional experiments.

The normal probability plot of the effects shows the standardized effects relative to a distribution fit line for the case when all the effects are 0. The standardized effects are \( t \)-statistics that test the null hypothesis that the effect is 0. Positive effects increase the response when the settings change from the low value of the factor to the high value. Negative effects decrease the response when they settings change from the low value of the factor to the high value of the factor.
3.2. Lenth’s plots

Lenth’s method is used to assess the effect of factors and based on factor sparsity. This method defines the pseudo standard error (PSE) (see Equation (4)) and the 95% margin of error (ME) (see Equation (5)).

\[
PSE = 1.5 \times \text{median} \left| c_j \right| \quad \left| c_j \right| < 2.5s_0
\]

\[
ME = t_{0.975,d} \times PSE
\]

where \( t_{0.975,d} \) is the 0.975th quantile of the t distribution with \( d = \frac{m}{3} \) degrees of freedom, \( c_1, \ldots, c_m \) are the estimated contrasts and \( s_0 = 1.5 \times \text{median} \left| c_j \right| \), is the approximate standard error.

Finally, the 95% simultaneous margin of error (SME) (see Equation (6)) is defined for simultaneous inference on all the contrasts.

\[
SME = t_{\gamma,d} \times PSE
\]

where \( \gamma = 0.5(1 + 0.95^{-m}) \) [41].

3.3. Bayesian screening

Bayesian screening is based on the factor sparsity hypothesis. For the linear model \( y = X\beta + \epsilon \), the procedure assigns prior normal distributions \( N(0, \gamma^2 \sigma^2) \) to each of the independent \( \beta_i \), where \( \gamma^2 \) is the magnitude of the effect relative to the experimental noise and \( \sigma^2 \) is the variance of the error. The assumption of the factor sparsity is manifested by assigning a prior probability \( \pi \) to any factor of being active and \((1 - \pi)\) to the factor of being inactive. The posterior probabilities of the models \( M_i \) for all subsets of factors are then calculated. Consequently, marginal factors posterior probabilities \( p_i \) are computed. Finally, the factor effects with higher probabilities are identified as potentially active [42, 43].

4. Results and discussion

The aim of this study is to determine the significant factors affecting creep of concrete. For that, a screening analysis of two-level factorial design was carried out and examined ten factors affecting concrete compliance. Figure 1 shows the half-normal plot of effects (Daniel Plot). In normal and half-normal plots, the factors “out of the straight line” are identified as potentially active factors; therefore, as seen in Figure 1, it is not clear which factors that may be active.

![Figure 1. Half-normal plot of effects.](image-url)
Lenth’s plot is presented in Figure 2 and as seen none of the effects goes beyond the margin of error ME, thus the SME limits are not displayed, so the identification of the active factors is not possible.

Figure 2. Lenth’s plot.

Figure 3 shows the results of Bayesian screening. The most individual factors affecting creep of concrete are ordered as follows: the mean compressive strength, the volume-surface ratio, the aggregate-cement ratio, the water-cement ratio, the presence of admixtures, the time of first loading, the content of cement, the cement type, the relative humidity and the sustained load.

Figure 3. Posterior probabilities of factors using Bayesian screening.

The analysis revealed interesting and controversial results showing the some major factors used in creep model predictions [34-37]. The model recommended by the ACI Committee 209 [34] does not require the most significant factor affecting creep which is the mean concrete compressive strength at 28 days because this model calculates the creep coefficient rather than the creep compliance, which may introduce problems due to the assumed value of elastic modulus. This model neglects the importance role of the aggregate-cement ratio and the water-cement ratio which are in the top five factors affecting creep of factors. The models proposed in [36] and [37] require the mean concrete compressive strength at 28 days and the volume-surface ratio but also ignore the role of the aggregate-cement ratio and the water-cement ratio. B3 model [35] requires the top factors affecting creep of concrete. It is important to notice the importance of admixtures in concrete on the results of compliance which in the top 5 of the factors affecting creep of concrete. For that, it is required in future works to present model creep for each admixture depending on its type and percentage/content.

5. Conclusions
Screening design was applied using Daniel Plot, Lenth’s Plot and Bayesian screening to examine the most significance factors affecting creep of concrete. This analysis considered experimental results
from the NU database. The data used is two-level factorial design of ten factors: water-to-cement ratio, aggregate-to-cement ratio, cement content, mean concrete compressive strength, effective thickness, age at loading, relative humidity, sustained stress, type of cement, and presence of admixtures. The top five individual factors include the mean compressive strength, the volume-surface ratio, the aggregate-cement ratio, the water-cement ratio and the presence of admixtures. None of ACI, CEB and Gardner models require the top 5 factors affecting creep of concrete while calculating the compliance. The analysis shows the major effect of the admixture in concrete as a main factor affecting creep. For that, it is required in future works to present model creep for each admixture depending on its type and its percentage content. The results of this analysis can be used to build accurate computational models to predict creep of concrete by considering the major effects identified in the analysis.

6. References

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