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PCM17 and PCM$_{17}$WR New Models For Predicting Creep of concrete Deformations

Phenomenological Creep Model 17 with and without water-reducing admixture

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Abstract— **Creep and shrinkage strains of concrete can have prejudicial consequences in structures. Often, the values of these uncontrolled strains appear to be clearly different from the expected ones. In fact, there is not yet a physical explanation perfectly satisfactory of creep and the codified descriptions of this phenomenon are always unreliable and don't take the effect of admixtures into consideration. In the context of this study, and starting from an important experimental database coming from international laboratories and research centers, new models of creep calculation were developed and allow to take the effect of water-reducing admixture into consideration and to obtain results more satisfactory than those of the Eurocode 2.**

Keywords—**creep, admixture, material, model, database**

I. Introduction

When working on the issue of concrete performance, the emphasis is usually put on a single parameter, specifically the strength. However, in some situations, some other parameters have an equal or greater importance, such as time-variant deformations. The prediction of the behavior of concrete structures with time is an extremely complex task, since chemical, physical and mechanical properties of concrete are substantially altered. In particular, the rheological behavior of concrete is itself time dependent. Mainly, the strains undergone by concrete can be classified into three categories: shrinkage strain, instantaneous strain and creep strain [1]. After the concrete has been cast, the shrinkage strain appears immediately and continue, with monotonically decreasing rate, over the whole lifetime of concrete member. Instantaneous strain is defined as the strain that appears immediately when the load is applied, whether they belong to the elastic or inelastic domains. Creep is defined as the increase of strain with time, for concrete under sustained load. The distinction between instantaneous strain and creep strain is not straightforward as it may seem, owing to the fact that the recorded instantaneous strain depends on the speed of application of the load and thus, inevitably, a portion of that strain is due to creep. However, such distinction will not be crucial in practical cases because what matters is the total strain incurred by the concrete member under study. The physical nature of creep is not yet well understood. Almost all creep code models are mainly of empirical nature, whose parameters are determined by experience.

In 1978, Bažant and Panula started collecting, at the Northwestern University (NU), shrinkage and creep data from all over the world. Their database contained approximately 400 creep tests and 300 shrinkage tests, mostly from North America and Europe. After the ACI-CEB Hubert Rush workshop on concrete creep [2], Müller and Panula extended this database as part of the collaboration established between the ACI and the CEB. A further expansion undertaken by the RILEM TC 107-CSP subcommittee 5 [3] led to what is known as the RILEM database. A major expansion leads to the current database completely restructured and verified, and named the NU Database [4]. The latest database was assembled at NU during 2010-2013 [5] mainly under the support of the U.S. Department of Transportation. Information was extracted from many reports, conference proceedings and journal articles.

The problem of evaluating existing models and code procedures received extensive attention in the literature. Raphael el al., in their study, prove that the creep predicted by the design codes is not satisfactory for long-term creep predictions [6]. Numerous papers proposed various statistical methods to evaluate and compare the predictive capability of these procedures [7].

In the present work, the database was grouped into categories according to the admixture used in the concrete composition. The experimental results of test without admixtures in this database are compared with the Eurocode 2 [8] design code of practice. As the comparison shows that this code overestimates the creep strain, a new creep model is proposed in this work on the basis of the experimental database. Moreover, since design codes of practice don't take the effect of admixtures into consideration, the experimental results of test with water - reducing admixture in this database are used to develop a new creep model taking the effect of the type and percentage of this admixture into consideration.

II. Evaluation of creep strains

A. *Experimental database*

Starting from a large experimental database collected from several research institutions all over the world and

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known as the NU database, a comparison is performed between the results obtained by laboratory tests and those given by the models indicated in the Eurocode 2 design code. The database includes creep tests on samples of various shapes and dimensions, under different environmental conditions. This database allows a validation of each creep model by quantified statistical analysis.

The tests in this database are performed by using different parameters [5] including, but not limited to, water to cement ratio, aggregate to cement ratio, cement type (α), compressive concrete strength at 28 days (f_{c28}), compressive concrete strength at the loading date ($f_{cm}(t_0)$), effective thickness, age at loading (t_0), temperature (T), relative humidity (ρ_h), sustained stress (σ), admixtures type, etc.

The compressive strength of concrete at 28 days f_{c28} (MPa) varies between 8 MPa and 105 MPa while the mean radius r_m of the specimen varies between 1.5cm to 13cm. Regarding the loading date t_0, it varies between 0.5 day and 3300 days. The relative ambient humidity ρ_h varies between 20% and 100%. The applied stress σ varies between 0.6 and 53 MPa. The duration of the test after the loading date ($t-t_0$) exceeds for some experiments 3000 days.

B. *Evaluation methods*

The creep compliance $J(t,t_0)$ is the time-dependent strain per unit stress. In order to evaluate the accuracy of the Eurocode 2 creep compliance prediction on the basis of the experimental tests, three methods have been applied, in which N means the total number of experiments, n the total number of measurement at fixed time j of experiment i, Cal $X_{ij,}$ the predicted creep compliance at time j of experiment i, and Obs X_{ij} the experimental creep compliance at time j of experiment i,.

1) The M_{CEB} method

The M_{CEB} method aims at calculating the mean deviation and indicates if a model overestimates or underestimates systematically the experimental values [9]. It may be calculated using the following formulas:

$$M_i = \frac{1}{n}\sum_{j=1}^{n}\frac{CalX_{ij}}{ObsX_{ij}} , \qquad (1)$$

$$M_{CEB} = \frac{\sum_{i=1}^{N} Mi}{N} . \qquad (2)$$

When the M_{CEB} coefficient is near 1, the values of the predicted compliance are close to the experimental results. If the M_{CEB} coefficient is less than 1, then the Eurocode 2 underestimates the strains. Contrary, if the M_{CEB} coefficient exceeds 1, this means that the Eurocode 2 overestimates the strains. In this study, we have obtained an M_{CEB} = 1.54, which indicates that the Eurocode 2 overestimates the creep compliance.

2) The V_{CEB} method

The V_{CEB} method calculates an average coefficient of variation in order to evaluate a model relatively to the experimental database. By considering Y_i as the average value of creep of experiment i, Y_{ij} as the experimental creep at time j of experiment i, $\Delta Y_{ij,}$ as the difference between the experimental and predicted creep compliance at time j of experiment i, S_i as the standard error of ΔY_{ij} of experiment i, and V_{CEB} as the average coefficient of variation, then the V_{CEB} may be calculated using the following formulas:

$$Y_i = \frac{\sum_{j=1}^{n} Y_{ij}}{n} , \qquad (3)$$

$$S_i = \sqrt{\frac{1}{n-1}\times\sum_{j=1}^{n}\left(\Delta Y_{ij}\right)^2} , \qquad (4)$$

$$V_i = \frac{S_i}{Y_i}\times 100 , \qquad (5)$$

$$V_{CEB} = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{N} V_i^2\right)} . \qquad (6)$$

Small values of V_{CEB} show that the predicted creep compliance are equal to the experimental creep compliance. In this study, we have obtained a V_{CEB} = 197, which indicates that the Eurocode 2 does not estimate accurately the creep compliance.

3) The F_{CEB} method

The F_{CEB} method calculates the mean square error of the predicted values. By considering f_j as the difference in percentage between the predicted and experimental values and F_{CEB} as the mean square error, then the F_{CEB} may be calculated by using the following formulas:

$$f_j = \frac{(CalX_{ij} - ObsX_{ij})}{(ObsX_{ij})}\times 100 , \qquad (7)$$

$$F_i = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n} f_j^2} , \qquad (8)$$

$$F_{CEB} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} F_i^2} . \qquad (9)$$

Similar to V_{CEB}, small values of F_{CEB} show that the predicted creep compliance are equal to the experimental creep compliance. In this study, F_{CEB} = 415, which indicates that the Eurocode 2 does not estimate accurately the creep compliance.

C. *Interpretation of Results*

The results obtained by comparing the creep compliance predicted by the Eurocode 2 to the experimental measurements using the CEB statistical methods show that the Eurocode 2 overestimates the creep compliance. Therefore, there is a need for a predictive model with better performance to anticipate accurately the deformations of structures. Moreover, there is a need for a new model that takes the effect of admixtures into consideration in predicting creep compliance since design codes don't.

III. New Models (PCM17 and PCM$_{17}$WR)

A. *Proposed models*

The proposed models are based on the observation of physical behavior of creep phenomenon. It targets at expressing the creep compliance in terms of the structural and environmental parameters. The experimental observations show clearly two kinetic regimes in logarithmic time scale (Fig. 1). The first one is a kinetic regime for short term (few days after loading) where the creep increases quickly and the second one is a kinetic for long-term where the creep increases with a lower rate which is almost constant, leading to large increase over structural lifetime. These two regimes suggest an additive form of the corresponding creep strains. Raphael et al., in their study, [6] have used this description to propose a new model called Phenomenological Creep Model based on the RILEM, LCPC and CEBTP database. In this study, based on a new experimental database, the NU database, an update of the Phenomenological Creep Model is performed and a new model taking the effect and percentage of water - reducing admixture is proposed. That's why the proposed new models are called *Phenomenological Creep Model 2017 (PCM17)* and *Phenomenological Creep Model Water Reducer (PCM$_{17}$WR).*

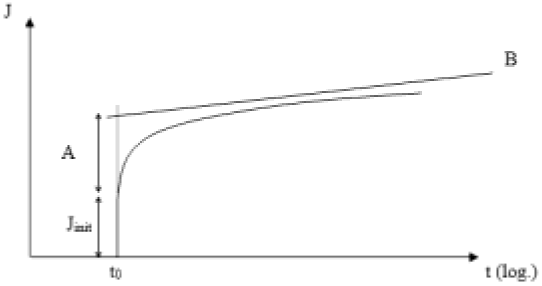

Figure 1. Shape of the curve of the total creep

In order to determine the best fitting of creep evolution, we have considered the database specimens. The database will serve for both calibration and validation of the proposed model.

To consider the two creep kinetics within an additive expression, an analysis of the experimental results in the database was performed in order to develop the best nonlinear mathematical model for predicting creep. In a semi-logarithmic scale, this analysis has converged at the following expression for the compliance J(t,t$_0$):

$$J(t,t_0) = J_{init} + A \times (1 - e^{\frac{-(t-t_0)}{30}}) + B \times \log_{10}(\frac{t}{t_0}) \quad . (10)$$

where t is the time in days, t$_0$ is the loading time in days, J(t,t$_0$) is the compliance which characterizes the creep strain per unit stress, and J$_{init}$ is the compliance value at t = t$_0$ (J$_{init}$ is the instantaneous creep strain per unit stress); the units of J(t,t$_0$) and J$_{init}$ are MPa^{-1}. The parameters A and B have to be calibrated on the basis of experimental data. This equation describes the PCM17 and PCM$_{17}$WR. The difference between the two models is presented in the expressions of A, B and J$_{init}$.

As shown in Fig. 1, the parameter A represents the amplitude at short-term creep and the parameter B represents the long-term creep rate. Equation (10) is the sum of three terms, as it can be seen in Fig. 2:

- the first term is constant J$_{init}$ allowing to take account for instantaneous creep strain at loading;
- the second term is exponential in elapsed time after loading, characterizing the evolution of short term creep;
- the third term is logarithmic in time, characterizing the evolution of long-term creep.

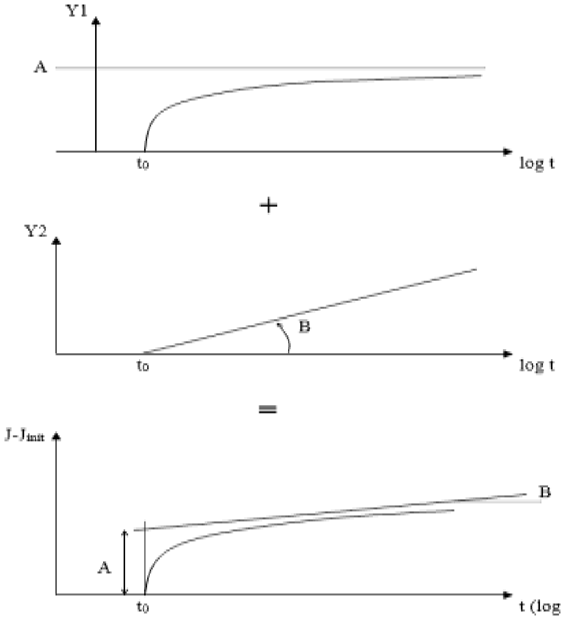

Figure 2. Shape of the creep curve, graphic sum of two terms (EXP + LOG)

In order to show the high capacity of the new models in fitting the experimental data, Fig 3 compares the experimental results of creep testing with the curve given by (10), using the software Curve Expert. The same analysis is performed for all the experimental set. In most cases, the PCM17 and PCM$_{17}$WR gave a very high fitting correlation, as in Fig.3. It has been noticed that the correlation coefficients of the regression vary between 0.9 and 0.99 with a mean value of 0.97, which is very good for confidence in results.

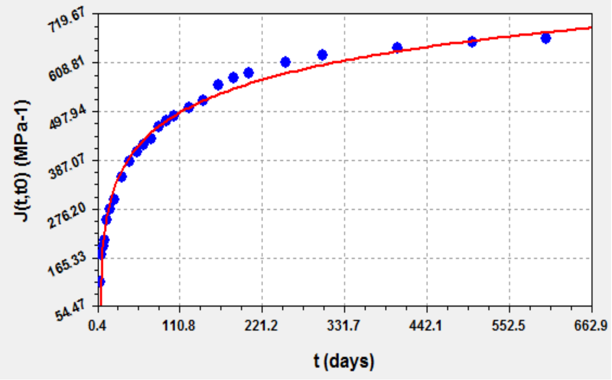

Figure 3. Example of PCM17 experimental fitting using the software Curve Expert

B. *Calibration of the new models parameters*

The proposed creep models PCM17 and PCM$_{17}$WR (10) depend on two parameters: A and B which should be calibrated using the experimental results. As mentioned previously, and using the software Curve expert, the values of the two parameters A and B are obtained by the minimization of the mean square error between predictive and experimental points. Therefore, we have a set of parameters (A, B, J$_{init}$) for each experiment in the selected database tests. Each set depends on the corresponding test configuration, and instead of considering average values for all experiments, we have chosen to express these parameters in terms of testing conditions, which are identified as:

- the temperature T (°C)
- the loading date t_0 (days)
- the compressive concrete strength at 28 days f_{c28} (MPa)
- the relative ambient humidity ρ_h (%)
- the mean radius r_m (m)
- the type of cement α
- the compressive strength of concrete at the loading date $f_{cm}(t_0)$ (MPa)
- the applied stress σ (MPa)
- the percentage and type of admixture

For all the sets of parameters (A, B, J$_{init}$), the regression procedure is applied to define the relationships between these parameters and the testing conditions influencing creep behavior. The following equations allow to express the parameters A, B and J$_{init}$ as functions of the structural configuration. The first set (11,12,13) corresponds to concrete without admixtures while the second set (14,15,16) refers to concrete with water – reducing admixture.

Results for PCM17 model:

$$J_{init} = 2.709T - 0.3066\alpha - 0.00915\sigma - 0.928\ln(t_0) - 0.0929\rho_h$$

$$+0.1946r_m - 16.6484\ln\left(f_{cm}(t_0)\right) - 0.1298f_{c28} + 53.064 \quad (11)$$

$$A = 4.572T - 1.835\alpha + 12.041\ln(\sigma) - 0.0104t_0 - 0.5033\rho_h$$

$$-1.582r_m + 0.27f_{cm}(t_0) - 33.5622\ln\left(f_{c28}\right) + 58.$$

(12)

$$B = -62.959\ln(T) + 2.7086\alpha - 0.219\sigma + 0.00874t_0 - 0.13\rho_h$$

$$-0.768r_m - 9.793\ln\left(f_{cm}(t_0)\right) + 0.04f_{c28} + 246.638$$

(13)

Results for PCM$_{17}$WR model:

$$J_{init} = 0.035T + 1.288\alpha - 7.7\ln(\sigma) + 1.7\ln(t_0) - 11.349\ln(\rho_h)$$

$$+0.0019r_m - 0.073f_{cm}(t_0) + 2.4\ln\left(f_{c28}\right) - 0.39WR + 88.537 \quad (14)$$

$$A = 0.277T - 0.108\alpha + 34.2462\ln(\sigma) + 2.37\ln(t_0) - 27.316\ln(\rho_h)$$

$$+5.04r_m - 0.238f_{cm}(t_0) - 0.117f_{c28} - 5.15WR + 44.72$$

(15)

$$B = -0.17T + 2.755\alpha - 0.29\sigma + 0.047t_0 + 9.88\ln(\rho_h)$$

$$-4.528r_m - 11.226\ln\left(f_{cm}(t_0)\right) - 2.58\ln\left(f_{c28}\right) - 0.399WR + 36.54$$

(16)

It is to note that this model is original as it takes into account the structural, environmental parameters and admixtures, observed from testing, which is new compared to the available models in literature. It has also the advantage of taking account for specific site conditions of the infrastructure, in addition to materials and loading characteristics.

C. *Validation of PCM17 and PCM$_{17}$WR creep models*

In order to validate the new PCM17 and PCM$_{17}$WR models, the creep compliances predicted by the proposed new creep models are compared with the experimental measurements issued from the database. In order to evaluate the PCM17 and PCM$_{17}$WR accuracy, the CEB statistical methods were applied.

In Table 1, the CEB statistical methods are calculated for the Eurocode 2 and the PCM17 model in the collected database.

TABLE I. CEB STATISTICAL RESULTS FOR EUROCODE 2 AND PCM17 MODEL

	***M$_{CEB}$* (expected value 1)**	***V$_{CEB}$* (expected value 0)**	***F$_{CEB}$* (expected value 0)**
Eurocode 2	1.54	197	415
PCM17	1.06	85.8	143.35

It can be clearly observed that the PCM17 predictions are very accurate as the mean deviation M$_{CEB}$ is closer to 1. Moreover, the coefficient of variation V$_{CEB}$ has decreased from 197 to 85.8 and the mean square error F$_{CEB}$ also has decreased from 415 to 143.35 by applying the PCM17 model compared to the Eurocode 2 model.

In Table 2, the CEB statistical methods are calculated for the $PCM_{17}WR$ model in the collected database.

TABLE II. CEB STATISTICAL RESULTS FOR $PCM_{17}WR$ MODEL

	M_{CEB} *(expected value 1)*	V_{CEB} *(expected value 0)*	F_{CEB} *(expected value 0)*
$PCM_{17}WR$	0.99	28.64	166

It can be clearly observed that the $PCM_{17}WR$ predictions are very accurate as the mean deviation M_{CEB} is almost equal to 1. Moreover, the coefficient of variation V_{CEB} and the mean square error F_{CEB} have small values.

The above results lead to the following conclusions:

- The proposed Phenomenological Creep Model PCM17 provides better results than the Eurocode 2.
- The proposed Phenomenological Creep Model $PCM_{17}WR$ allows to take the effect of water-reducing admixture into consideration.
- In addition to the above observations, the PCM17 and $PCM_{17}WR$ allow us to evaluate accurately the initial creep compliance J_{init} by taking into account a number of structural parameters, not only the concrete strength as given in most of design codes, especially Eurocode 2.

IV. Conclusion

In this work, a large creep database has been adopted in order to develop and to validate new models for creep predictions. The comparison between the experimental results and the Eurocode 2 code of practice has shown that creep strains are overestimated in this code. Moreover, the Eurocode 2 does not take the effect of admixtures into consideration in predicting the creep compliance.

The proposed models, called the Phenomenological Creep Models PCM17 and $PCM_{17}WR$, are based on the analysis of creep tests in the database and on the physics of the creep behavior, which is divided into exponential time function for short-term creep evolution and logarithmic time function for long-term creep evolution. The proposed formulations are given as a function of the material, loading and environmental parameters. The comparison with experimental data shows the high accuracy of the proposed models. The PCM17 and $PCM_{17}WR$ improve largely the prediction of creep strains, compared to the existing code of practice.

In the future, it would be also interesting to study the effect of admixtures other than water reducer and to analyze the effect of prediction accuracy on the reliability assessment of existing infrastructures.

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References

[1] W. Raphael, and A. Chateauneuf, "Étude du fluage des structures en béton armé et précontraint" – Nouveau Modèle et Calculs fiabilistes, Editions Universitaires Européennes EUE, 2011.

[2] H.K. Hillsdorf, and D.J. Carreira, "ACI-CEB conclusions of the Hubert Rüsch Workshop on Creep of Concrete", Concrete international, vol. 2 no. 11, 1980, pp.77.

[3] H.S Müller, Z.P. Bažant, and C.H. Kuttner, "Database on creep and shrinkage tests", Rilem subcommittee 5 Report Rilem TC107-CSP, RILEM, Paris, 1999.

[4] *NU (Northwestern University) NU database of laboratory creep and shrinkage data*. www.civil.northwestern.edu/people/bazant.

[5] M.H. Hubler, R. Wendner, and Z.P. Bažant, "Comprehensive database for concrete creep and shrinkage: Analysis and recommendations for testing and recording". ACI Materials Journal, vol 112, no.4, 2015, pp. 547-558.

[6] W. Raphael, F. Kaddah, F. Geara, and A. Chateauneuf, "Information-based modeling of creep in concrete structures." ICOSSAR, 11th International Conference On Structural Safety And Reliability, New-York – USA, 2013

[7] A. Chateauneuf, W. Raphael, and R.M. Pitti, "Reliability of prestressed concrete structures considering creep models." Structure and Infrastructure Engineering, vol 10, no. 12, 2014, pp. 1595-1605.

[8] CEN, EN 1992-1-1: Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings. CEN, Brussels, Belgium, 2004.

[9] American Concrete Institute, *ACI 209.2R-08 Guide for Modeling and Calculating Shrinakge and Creep in Hardened Concrete*. American Concrete Institute, Farmington Hills, MI, USA, 2008.

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