EVALUATION OF THE CREEP COEFFICIENTS OF THE FIB 2010 AND RILEM B4 CONCRETE CREEP PREDICTION MODELS

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SUMMARY

Creep of concrete is an important design consideration. National design codes therefore provide empirical based models for the estimation of creep deformation. Such models generally estimate a creep coefficient (ϕ) and an elastic modulus (E) of the concrete, both of which are used to predict the creep strain at any age. This paper assesses the accuracy of the creep coefficients (ϕ) predicted by the relatively new international fib Model Code 2010 (MC 2010) and RILEM Model B4 using a laboratory test programme. The measured creep coefficient (ϕ) values were statistically compared to those predicted by the models considered. The MC 2010 (2012) Model, which yielded an overall coefficient of variation (ω_{all}) of 44.9 %, was found to be more accurate than the RILEM Model B4 (with a (ω_{all}) of 103.3 %). Both the models validated were found to yield less accurate creep coefficients than their respective predecessor models.

1. INTRODUCTION

Creep magnitude is an important design consideration for the durability, long-term serviceability and the load carrying capacity of structures.

The magnitude of creep can be determined by laboratory testing or estimated by means of empirical based models of various complexities. In general, the more deformation sensitive the structure, the more justifiable the cost and time of laboratory testing or complexity of the estimation method employed. In cases where only a rough estimate of the creep is required, design code-type models are ideal for predicting the creep

With the exception of the RILEM Model B3 (1995), creep models express creep strain in terms of the creep coefficient, (ϕ), where:

$$\varepsilon_c(t, \tau) = \varphi(t)\, \varepsilon_{e,\tau} \qquad (1)$$

In Equation 1, $\varepsilon_c(t, \tau)$ is the creep strain at any concrete age t for a concrete loaded at age τ, where $t > \tau$ and $\varepsilon_{e,\tau}$ is the elastic strain of the concrete at age τ. The creep coefficient (ϕ) is empirically determined by considering one or more intrinsic and/or extrinsic variables such as concrete stiffness and age at first loading. The elastic modulus used to estimate the elastic strain is estimated using an empirical equation prescribed by that method.

The RILEM Model B3 (1995) and RILEM Model B4 (2015) are, by comparison, more complex than the design code models and take a more fundamental materials approach to creep prediction. In the case of these models, an elastic modulus is estimated, which is used in the calculation of the compliance function for additional creep due to drying and may be used to calculate the creep coefficient ($\phi_{(t)}$) from the relevant compliance function equations (by dividing ε_c by ε_e).

Previous work by Fanourakis (1998), Fanourakis and Ballim (2006), Fanourakis (2011) and Fanourakis (2016) collectively assessed the accuracy of fifteen code-type creep prediction models when applied to South African concretes.

Fanourakis (2011) investigated the correlation between the predicted specific creep (Cc) and the estimated elastic (E) and established that most accurate creep prediction model, the CEB-FIP (1970), (for the Cc) was the least accurate in estimating elastic modulus (E). Furthermore, the models that yielded the most accurate estimation of elastic modulus (E) (SANS 10100, 2000 and AS 3600, 2009) did not yield the most accurate estimation of specific creep (Cc).

Subsequently, Fanourakis (2016) established that a highly significant (P = 0.001 %) correlation (r = 0.901) exists between the creep coefficient (ϕ) and specific creep (Cc) predicted by the fourteen models considered.

This paper assesses the accuracy of the creep coefficients estimated by the relatively new fib Model Code 2010 (2012) and the RILEM Model B4 (2015), when compared with the actual creep coefficients measured on a range of South African concretes under laboratory controlled conditions, for a period of approximately six months. These concretes included two strength grades (w/c's of 0.56 and 0.4) and three aggregate types (quartzite, granite and andesite).

The accuracy of the fib Model Code 2010 (MC 2010) and RILEM B4 (2015) Models was compared to the accuracy of their predecessor models.

2. MODELS INVESTIGATED

The two relatively new models evaluated in this investigation were the fib Model Code 2010 (MC 2010) and RILEM B4 Model (2015).

The Comité Euro-International Du Béton - Federation Internationale De La Précontrainte (CEB-FIP) Model Code (2010), fib Model Code 2010 (MC 2010), superseded the CEB-FIP (1990) model, which was in turn superseded by the CEB Model Code 90-99 which accounted for particular characteristics pertaining to high strength concretes.

The RILEM Model B3 (1995) was superseded by the RILEM Model B4 (2015), which accounts for additional parameters including the cementitious material type, admixtures and aggregate type (Wendner et al., 2013).

3. EXPERIMENTAL DETAILS

3.1 Materials

CEM I 42,5 cement, from the Dudfield factory of Alpha Cement (now AfriSam), was used for all the tests carried out in this investigation. Quartzite (Q) from the Ferro quarry in Pretoria, granite (G) from the Jukskei quarry in Midrand and andesite (A) from the Eikenhof quarry in

Johannesburg were used as both the coarse and fine aggregates for the concrete. The stone was 19 mm nominal size and the fine aggregate was crusher sand.

3.2 Preparation of prisms

For each of the concretes, six prisms were prepared, measuring 100 x 100 x 200 mm and cast with the 200 mm dimension vertical. After de-moulding, these prisms were continuously water cured up to an age of 28 days. After curing, three of the six prisms of each mix were used for creep tests and the remaining three were used for shrinkage measurements.

3.3 Elastic Modulus measurements

The creep test prisms were stacked into creep loading frames and subjected to elastic strain measurements, within 10 minutes of application of the loads, which were used to determine the secant moduli of the concretes.

3.4 Creep and shrinkage measurements

The creep tests commenced immediately after the elastic modulus measurements were taken. These tests entailed subjecting the prisms in each frame to an applied load of approximately 25 % of the 28-day compressive strength, for the 168 day period, in a room controlled at 22 ± 3 °C and RH of 65 ± 5 %.

The shrinkage (companion) prisms were placed on a rack in the same room as the creep samples and, in order to ensure a drying surface area equivalent to the creep samples, the two 100 mm square ends were dipped in warm wax to prevent drying from these surfaces.
Creep and shrinkage measurements were recorded daily for the first week, thereafter, weekly for the remainder of that month and then monthly until the culmination of the approximately six-month total loading period. The strain of each group of prisms, that is the three creep prisms or the three companion shrinkage prisms of a particular mix, was taken as the average of the strains of the prisms in that group.
The results of shrinkage measurements were subtracted from the total time-dependant strain of the loaded specimens to determine the total creep strain.

3.5 Mix details

Details of the mixes used are given in Tab. 1.

Tab. 1. Details of the mixes and laboratory test results (after Fanourakis, 2011)

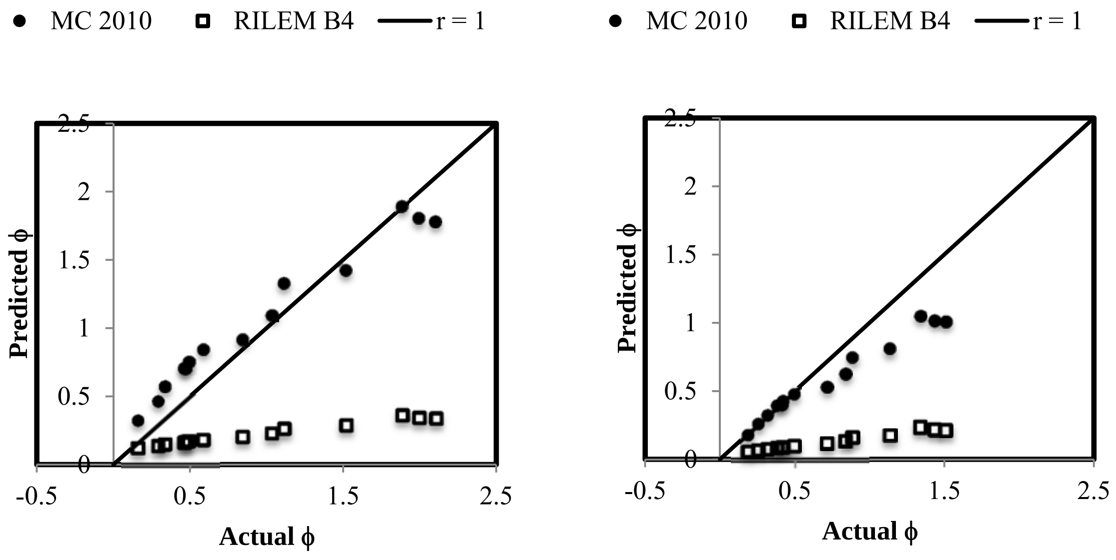
Aggregate Type	**Quartzite**		**Granite**		**Andesite**	
Mix Number	**Q1**	**Q2**	**G1**	**G2**	**A1**	**A2**
Water (l/m^3)	195	195	195	195	195	195
CEM I 42,5N (kg/m^3)	348	488	348	488	348	488
19 mm Stone (kg/m^3)	1015	1015	965	965	1135	1135
Crusher Sand (kg/m^3)	810	695	880	765	860	732
w/c Ratio	0.56	0.4	0.56	0.4	0.56	0.4

a/c Ratio	5.24	3.50	5.30	3.55	5.73	3.83
Slump (mm)	90	50	115	70	95	55
Cube Compressive Strength (MPa)	37	65	38	65	48	74
Cylinder Compressive Strength (MPa)[a]	30	53.5	30.7	53.5	38	59
Characteristic Cube Strength (MPa)	30	50	30	50	30	50
Characteristic Cylinder Strength (MPa)[a]	25	40	25	40	25	40
Concrete Density (kg/m^3)	2371	2410	2385	2432	2596	2585
Average Elastic Modulus of included Aggregate (GPa)	73		70		89	
[a] Inferred from cube strength using the conversions from EC 2 (2004)						

4. RESULTS AND DISCUSSION

4.1 Predicted versus actual ϕ values

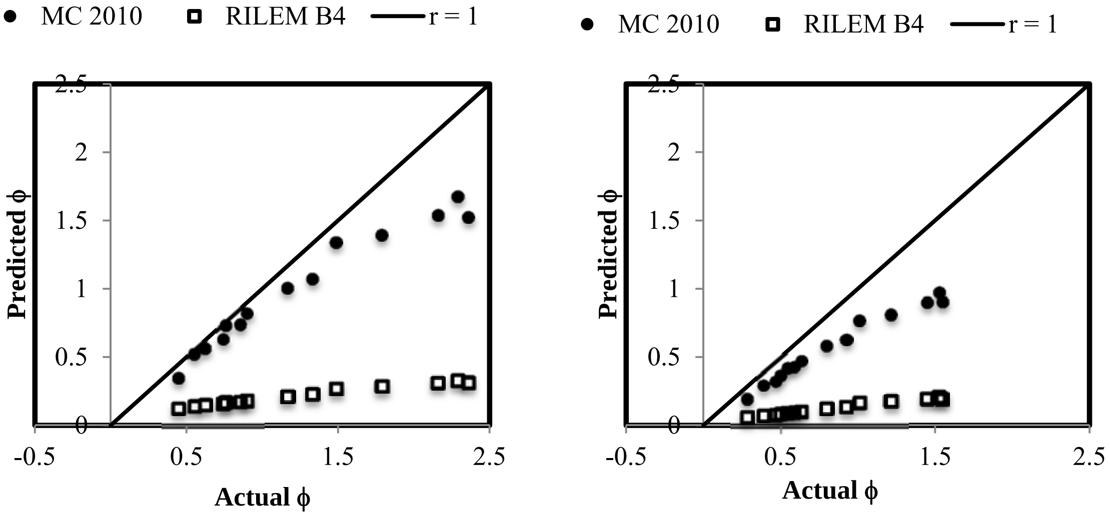
Figs. 1 to 3 show the relationships between the predicted ϕ and actual ϕ for the six mixes (Q1, Q2, G1, G2, A1 and A2), pertaining to the MC 2010 (2012) and RILEM B4 (2015) Models. The "r = 1" line (predicted equals actual) is included in each figure to display the relative accuracy of the predicted values.



(a) Mix Q1

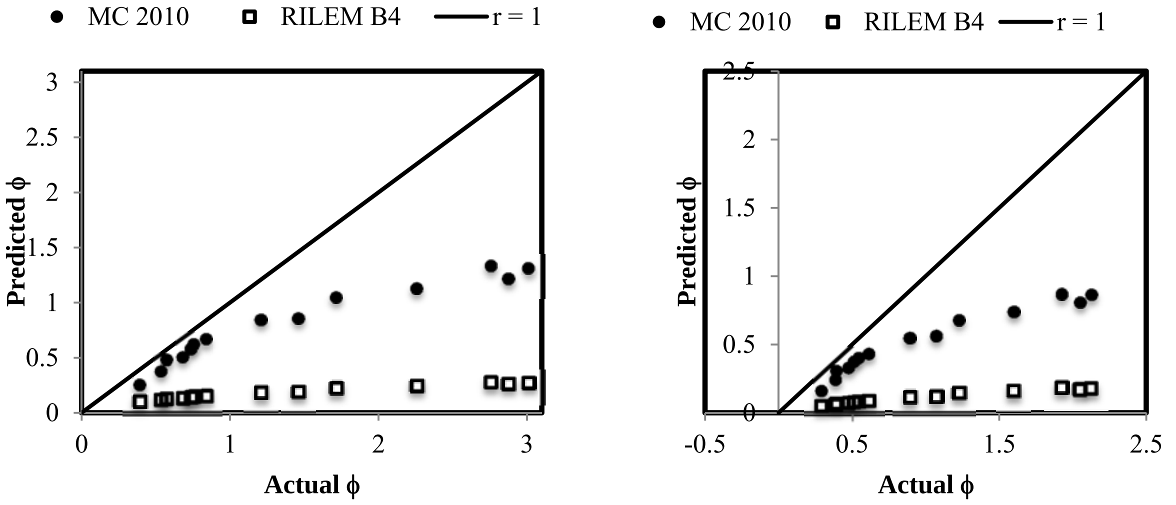
(b) Mix Q2

Fig. 1. Predicted versus actual creep coefficients (ϕ) for quartzite concretes



(a) Mix G1 (b) Mix G2

Fig. 2. Predicted versus actual creep coefficients (ϕ) for granite concretes



(a) Mix A1 (b) Mix A2

Fig. 3. Predicted versus actual creep coefficients (ϕ) for andesite concretes

From Figs. 1 to 3, the following is evident.

- Both the models considered general under-predicted the creep coefficients (ϕ).
- The MC 2010 (2012) Model predicted the ϕ values more accurately than the RILEM Model B4 (2015) Model, in the case of all six mixes.
- The variation in predicted ϕ values, with time, in the case of the RILEM Model B4 (2015) was relatively low (low rate of creep).
- The MC 2010 (2012) Model was the least accurate in the case of the andesite concretes (mixes A1 and A2), where the accuracy of the predicted ϕ values decreased after 7 days, indicating a decrease in the rate of creep.

- The trend lines pertaining to the MC 2010 (2010) model and RILEM B4 (2015) Models yielded pooled correlation coefficients (r) of 0.983 (0.967 to 0.987) and 0.988 (0.984 to 0.989), respectively.
- All the correlations established were highly significant, being at the P = 7.1E-06 % and P = 1.4E-07 % levels, in the case of the MC 2010 (2010) Model and RILEM B4 (2015) Models, respectively.

4.2 Accuracy of the models assessed

In order to provide a statistical basis for comparing the results of creep prediction methods, Bazant and Panula (1979) define a coefficient of variation of errors (ω_j) for single data sets as well for a number of data sets compared against the same prediction model (ω_{all}). The more accurate the prediction, the lower the value of ω_j. The calculated values of ω_j and ω_{all} for the different models assessed are shown in Tab. 2.

Tab. 2 Coefficients of variation for ϕ of the MC 2010 and B4 Models

Prediction Method	Coefficients of Variation (ω_j□)						ω_{all}
	Mix Q1	Mix Q2	Mix G1	Mix G2	Mix A1	Mix A2	
Fib Model Code 2010 (2012)	22.1	31.5	29.4	39.7	61.9	66.0	44.9
RILEM Model B4 (2015)	100.7	100.9	98.0	99.1	109.7	110.6	103.3

From Tab. 2, it is evident that the RILEM Model B4 (2015) was the least accurate of the two models assessed with a ω_{all} of 103.3 %. Both models yielded (slightly) more accurate predictions in the case of the low strength mixes.

4.3 Comparison with predecessor models

When comparing the accuracy of creep coefficient (ϕ) predictions, the CEB-FIP (1990) was more accurate than the succeeding MC 2010 (2012), yielding a ω_{all} of 27.7 %. Similarly, the RILEM Model B3 (1995) was more accurate than the succeeding RILEM B4 (2015) model, yielding a ω_{all} of 40.8 % (Fanourakis, 2016). Furthermore, for the mixes used, the RILEM B4 (2015), which is the most complex of all the models validated by the author, was the least accurate of the seventeen models considered in all the investigations.

5. CONCLUSIONS

- Both the models considered general under-predicted the creep coefficients (ϕ).
- The MC 2010 (2012) model predicted the ϕ values more accurately than the RILEM Model B4 (2015) model, in the case of all six mixes.
- The trend lines pertaining to the MC 2010 (2010) and RILEM B4 (2015) Models yielded pooled correlation coefficients (r) of 0.983 (0.967 to 0.987) and 0.988 (0.984 to 0.989), respectively.
- Both the MC 2010 (2012) and RILEM Model B4 (2015) models were less accurate than the models that their predecessor CEB-FIP (1990) Model and RILEM Model B3, respectively.

- The RILEM Model B4 (2015), which yielded a ω_{all} of 103.3 %, was the most complex yet least accurate of all seventeen models validated by the author to-date.

6. REFERENCES

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