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VALIDATION OF THE FIB 2010 AND RILEM B4 MODELS FOR PREDICTING CREEP IN CONCRETE

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Abstract

Creep strain, a requirement of the concrete design process, is a complex phenomenon that has proven difficult to model. Although laboratory tests may be undertaken to determine the creep, these are generally expensive and not a practical option. Hence, empirical code-type prediction models are used to predict creep strain.

This paper considers the accuracy of both the relatively new international fib Model Code 2010 and RILEM Model B4, when compared with the actual strains measured on a range of concretes under laboratory-controlled conditions. Both models investigated under-estimated the creep strain. In addition, the MC 2010 Model, which yielded an overall coefficient of variation (ω_{all}) of 50.4%, was found to be more accurate than the RILEM B4 Model (with a ω_{all} of 102.3%).

Streszczenie

Odkształcenia pełzania, których znajomość jest niezbędna w procesie projektowania, są złożone i trudne do przewidywania. Można przeprowadzić testy laboratoryjne w celu określenia pełzania, jednak są one generalnie kosztowne. W związku z tym w projektowaniu stosowane są modele empiryczne dostępne w normach. W artykule analizowano dokładność stosunkowo nowego międzynarodowego modelu pełzania przedstawionego w Model Code 2010 i RILEM B4, w porównaniu z rzeczywistymi odkształceniami pełzania mierzonymi w betonach dojrzewających w warunkach laboratoryjnych. Model MC 2010, który przyniósł całkowity współczynnik zmienności (ω_{all}) wynoszący 50.4%, okazał się być dokładniejszy niż RILEM B4 (z ω_{all} 102.3%).

Keywords: **Creep; Concrete; Codes; MC2010; RILEM B4.**

1. INTRODUCTION

Creep of concrete is a complex phenomenon that has proven difficult to model. Nevertheless, for many reinforced and prestressed concrete applications, a reasonably accurate prediction of the magnitude and rate of creep strain is an important requirement of the design process. Although laboratory tests may be undertaken to determine the deformation properties of materials, these are time consuming, often expensive and generally not a practical option. In addition, this is not often an option at the design stage of a project when decisions about the actual concrete to be used have not yet been taken.

Hence, empirical based design code type models are often used for the estimation of creep deformation, by considering one or more intrinsic and/or extrinsic variables such as concrete stiffness and age at first loading as input.

This paper assesses the accuracy of two such models, the fib Model Code 2010 [1] and the RILEM Model B4 [2], when compared with the actual strains measured on a range of South African concretes which were subjected to a compressive strength related uniform load, under laboratory controlled conditions (relative humidity and temperature), 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) [1] and RILEM B4 [2] Models was compared to the accuracy of other models, which were assessed (using the same concrete mixtures) during previous investigations.

In the abovementioned assessments, the predicted and measured creep results were presented in the form of specific creep (C_c), which is the creep strain per unit stress, as defined by Equations 1 and 2.

$$C_c = \frac{\varepsilon_c(t)}{\sigma} \quad (1)$$

Which can also be expressed as:

$$C_c = \frac{\varphi(t)}{E} \quad (2)$$

Where: $\varphi(t)$ is the creep coefficient at time t,
E is the elastic modulus of the concrete.

2. MODELS INVESTIGATED

The two models evaluated in this investigation were the fib Model Code 2010 (MC 2010) [1] and RILEM B4 Model [2].

The Comitté Euro-International Du Béton – Federation Internationale De La Précontrainte (CEB-FIP) Model Code (2010), fib Model Code 2010 (MC 2010) [1], superseded the CEB-FIP (1990) model [3], which was in turn superseded by the CEB Model Code 90-99 [4] which accounted for particular characteristics pertaining to high strength concretes.

The RILEM Model B3 [5] was superseded by the RILEM Model B4 [2], which accounts for additional parameters including the cementitious material type, admixtures and aggregate type [6]. The RILEM B3 [5] AND B4 [2] Models are relatively complex in comparison to the creep prediction models of international design codes.

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 Table 1.

Table 1.
Details of the mixes and laboratory test results [12]

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	73	70	70	89	89

[a] Inferred from cube strength using the conversions from EC 2 [7]

4. RESULTS AND DISCUSSION

4.1. Specific Creep with Time

Figures 1 to 3 show the comparisons between the measured results for the six mixes (Q1, Q2, G1, G2, A1 and A2) and the corresponding strains predicted by the MC 2010 [1] and RILEM B4 [2] Models.

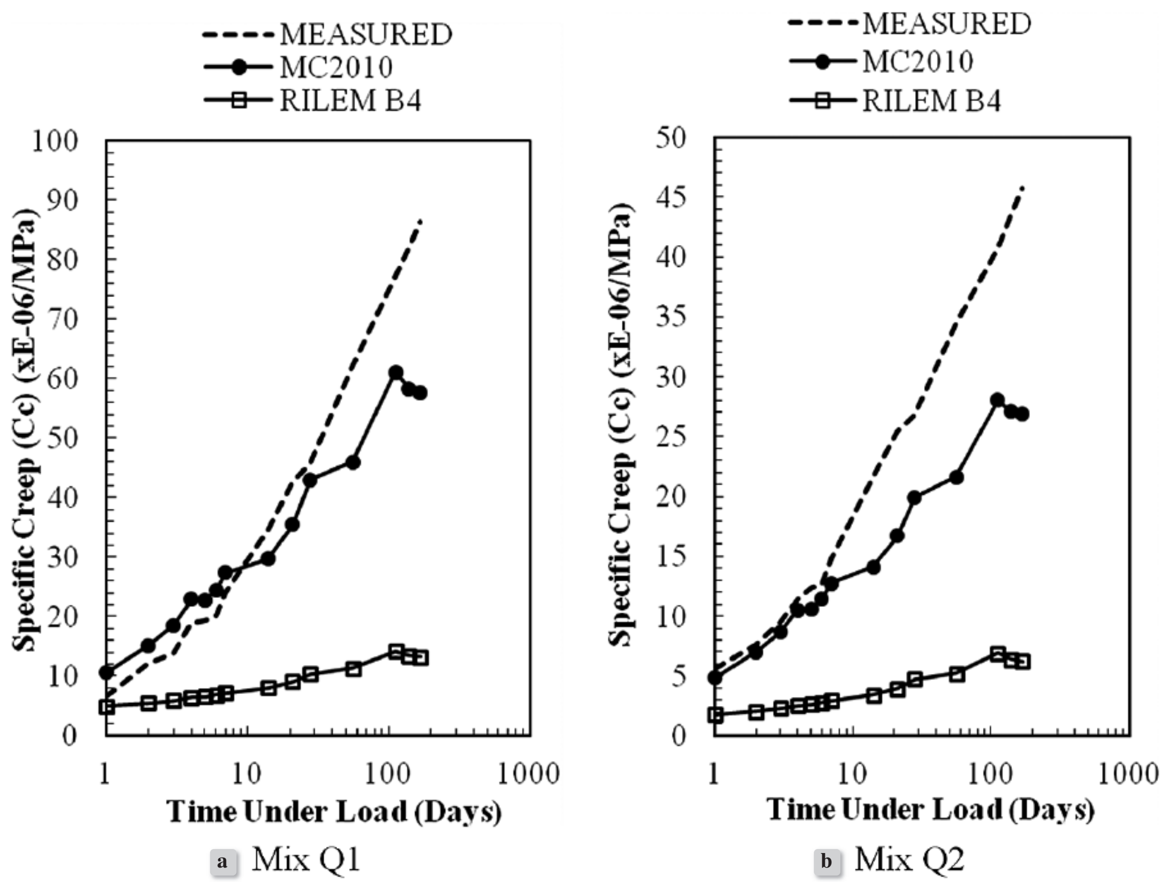

Figure 1.
Measured and predicted specific creep for quartzite concretes

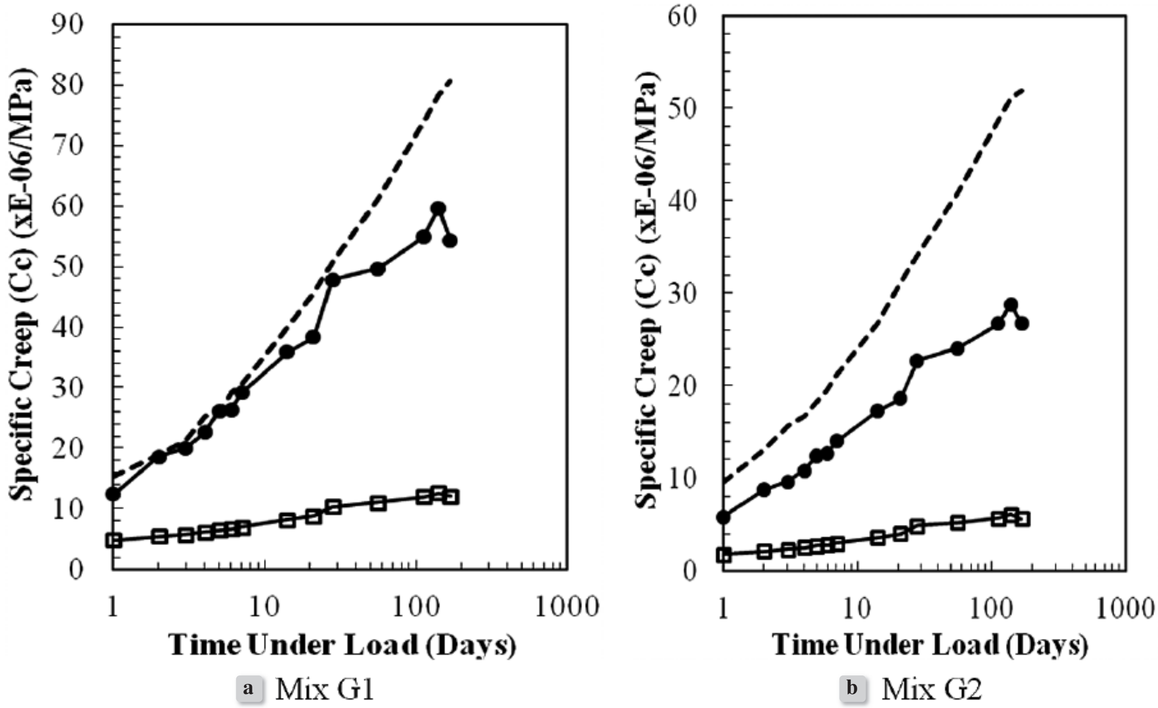

Figure 2.
Measured and predicted specific creep for granite concretes

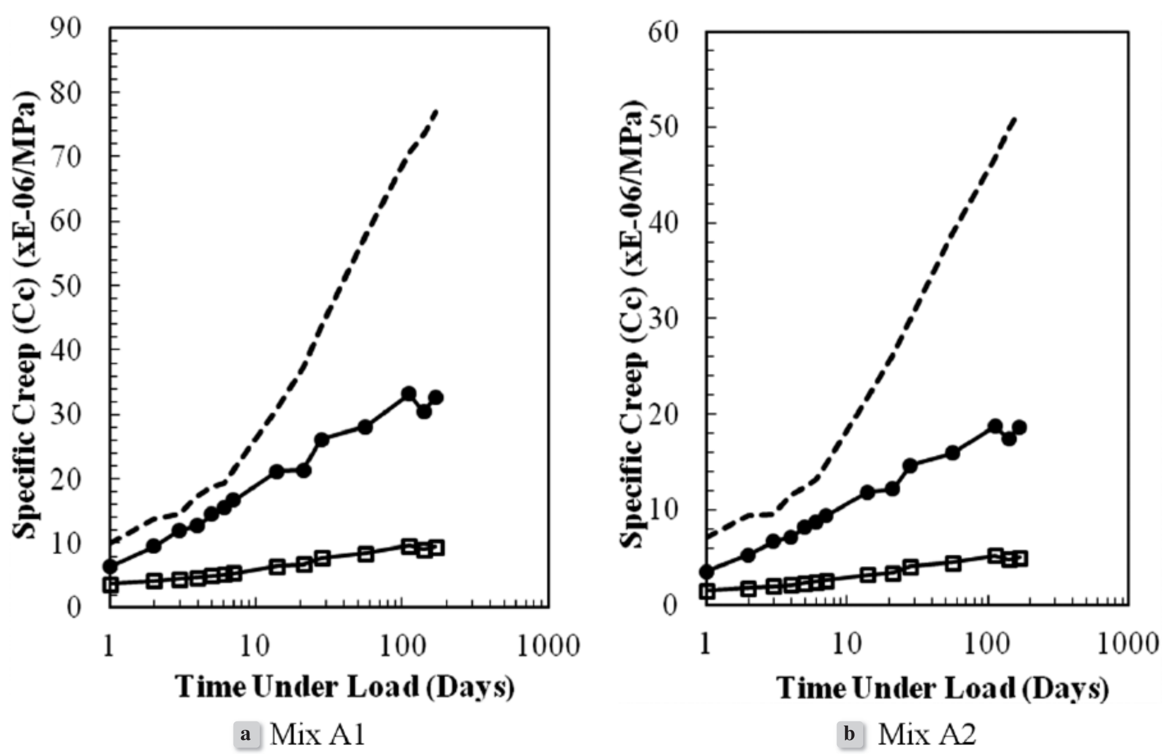

Figure 3.
Measured and predicted specific creep for andesite concretes

Table 2.
Coefficients of variation for specific creep of the MC 2010 [1] and B4 [2] Models

Prediction Method	Coefficients of Variation (ω_j)						ω_{all}
	Mix Q1	Mix Q2	Mix G1	Mix G2	Mix A1	Mix A2	
MC 2010 [1]	32.6	42.0	26.3	48.8	63.6	72.7	50.4
RILEM Model B4 [2]	102.1	101.9	95.9	101.4	105.0	109.0	102.3

From Figures 1 to 3, the following is evident regarding the prediction models.

- Both the MC 2010 [1] and RILEM Model B4 [2] models under-predicted the creep strain for all six of the concrete mixes.
- The MC 2010 [1] Model was more accurate than the RILEM Model B4 [2], in the case of all six mixes.
- In the case of each aggregate type, for both models, the mix with the lower w/c (0.4) yielded lower creep magnitudes than the mix with the higher w/c (0.56).
- In the case of the andesite concretes (A1 and A2), the rate of creep predicted by the MC 2010 [1] model did not increase after approximately one week of loading to replicate the trend observed in the case of the measured creep strains.
- In the case of all the mixes, the rate of creep predicted by the RILEM Model B4 [2] did not increase after approximately one week of loading to replicate the trend observed in the case of the measured creep strains.

When considering the effect of the aggregate type on the measured specific creep, the following was evident.

- For each aggregate type, the mix with the lower w/c ratio (stiffer mix) yielded relatively lower specific total creep values.
- No correlation was found to exist between the specific total creep strains and the stiffness of the included aggregate.

Detailed information regarding the effect of these aggregates on creep strain is given in Fanourakis and Ballim [8].

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 [9] 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 Table 2.

From Table 2, it is evident that the RILEM Model B4 [2] was the least accurate of the two models assessed with a ω_{all} of 102.3 %.

4.3. Comparison with the Accuracy of other Models

The coefficients of variation of other code-type models that were assessed during previous investigations by Fanourakis [10], Fanourakis and Ballim [11] and Fanourakis [12] are included in Table 3.

A comparison of the results in Table 3 with those of other investigations is included in Fanourakis and Ballim [13].

When comparing the accuracy of the MC 2010 [1] and RILEM B4 [2] Models, assessed in this paper, with other the accuracy of other models, it is evident that the MC 2010 [1] was less accurate than its predecessor CEB – FIP [3], which was only applicable to normal strength concretes. Furthermore, for the mixes used, the RILEM B4 [2], which was the most complex of all the models considered, was the least accurate of the seventeen models validated in all the investigations, including the model it superseded (Model B3 [5]).

In addition, Wendner et al., [14] found the relative accuracy of laboratory test total creep, of six models considered, to increase in the order GL 2000 [15], ACI 209 [16], MC 2010 [1], RILEM Model B3 [5], CEB–FIP 90-99 [4] and RILEM Model B4 [2]. The results of the two models investigated in this paper and those of previous investigations (shown in Table 3) agree with the relative order of accuracy of Wendner et al., [14], except in the case of the RILEM Model B4 [2] which was found to be the least (and not most) accurate of the six models.

Table 3.
Coefficients of variation for specific creep for various models

Prediction Method	Coefficients of Variation (ω_j)						ω_{all}
	Mix Q1	Mix Q2	Mix G1	Mix G2	Mix A1	Mix A2	
BS 8110 [17]	29	27.4	26.5	8.6	26.9	15.5	23.6
SABS 0100 [18]	20.1	41.4	26.5	8.6	47.9	26.5	31.3
SABS 0100 [18] modified	45.2	17.3	49.5	31.9	34.4	15.2	34.7
ACI 209 [16]	52.6	36.3	45.7	45.1	60.8	58.4	50.5
AS 3600 [19]	12.5	n/a	13.4	n/a	47.2	n/a	29.2
AS3600 [20]	67.4	16.6	51.1	13.2	25.5	25.8	38.6
AS3600 [21]	103.0	84.2	85.8	42.6	68.6	43.9	74.7
GL 2000 [15]	24.4	56.6	7.9	21.7	21.1	36.5	31.9
GL 2004 [22]	26.5	62.0	9.7	26.0	22.9	41.1	35.4
GZ [23]	58.4	46.8	46.3	37.4	55.7	49.8	49.5
CEB-FIP 1970 [24]	18.1	31.3	15.0	12.3	13.9	9.9	18.1
CEB-FIP 1978 [25]	66.0	148.6	53.9	95.1	65.6	112.8	96.1
CEB-FIP 1990 [3]	32.7	19.8	27.7	31.2	39.6	38.3	32.2
EC 2 [7]	28.0	26.5	20.8	38.3	35.3	45.5	33.4
RILEM Model B3 [5]	45.6	29.3	33.0	21.9	45.3	32.6	35.6

5. CONCLUSIONS

- Both the MC 2010 [1] and RILEM Model B4 [2] models under-predict the creep strain for all six of the concrete mixes.
- The MC 2010 [1] Model was more accurate than the RILEM Model B4 [2], in the case of all six mixes.
- Both the MC 2010 [1] and RILEM B4 [2] Models were less accurate than their predecessor CEB-FIP 1990 [3] Model and RILEM Model B3 [5], respectively.
- The RILEM Model B4 [2], which yielded a ω_{all} of 103.2%, was the most complex yet least accurate of all seventeen models validated by the author to-date.

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