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An assessment of the accuracy of nine design models for predicting creep in concrete

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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. National design codes therefore rely on empirical prediction models to estimate the magnitude and development of the creep strain.

This paper considers the suitability of nine 'design code type' creep prediction models when compared with the actual strains measured on a range of concretes under laboratory control conditions. The concretes tested incorporate three aggregate types and two strength grades for each aggregate type. The results are compared with the predictions of creep using models contained in BS 8110 (1985), SABS 0100 (1992), SABS 0100 (1992) modified, ACI 209 (1992), AS 3600 (1988), CEB-FIP (1970, 1978 & 1990), the RILEM Model B3 (1995) methods. The results indicate that the CEB-FIP (1970) and BS 8110 (1985) methods provide suitably accurate predictions over all the concretes tested. These methods yielded overall coefficients of variation of approximately 18 % and 24 %, respectively. The least accurate method was the CEB-FIP (1978) which yielded a coefficient of variation of approximately 96 %. The results of this investigation led to recommending the BS 8110 (1985) model for South African conditions.

INTRODUCTION

The magnitude of creep in concrete is a design consideration which is of importance for the durability, long-term serviceability and the load carrying capacity of structures. Its importance has been magnified by the recent tendency towards designing highly stressed and slender members.

The rate and ultimate magnitude of creep to be used in the design of a reinforced concrete structure can be estimated at various levels. The choice of level depends on the type of structure and the quality of the data available for the design. In cases where only a rough estimate of the creep is required, which is suitable only for approximate calculations, an estimate can be made on the basis of a few parameters such as relative humidity, age of concrete and member dimensions. On the other extreme, in the case of deformation-sensitive structures, estimates are based on comprehensive laboratory testing and mathematical and computer analyses. Ideally, a compromise has to be sought between the simplicity of the prediction procedure and the accuracy of results obtained (Bazant & Baweja 1994).

At the design stage, when often the only information available is the compressive strength of the concrete, the general environmental conditions of exposure and the member sizes, the designer has to rely on a design code model to estimate the extent and rate of creep strains. Given their nature, these models are not able to account for the full range of factors that are known to influence the creep deformation in concrete and simplicity of application is usually demanded by the users of the model. Nevertheless, the users of the model require some confidence as to the accuracy of the predictions as well as the range of error of the prediction.

This paper presents an assessment of nine concrete creep prediction models. Eight of these are commonly used international code-type models which are used to predict creep strains without the need for creep tests. These are the

- South African Bureau of Standards, SABS 0100 (1992), currently renamed SANS 10100 (2000)
- British Standards Institution – Structural Use of Concrete, BS 8110 – Part 2 – (1985)
- American Concrete Institute (ACI) Committee 209 (1992)

Keywords: Creep, predictions, models, aggregates, stiffness

Table 1 Details of the mixes, slump and 28-day compressive strength results for the concretes used in the investigation

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)	1 015	1 015	965	965	1 135	1 135
Crusher sand (kg/m^3)	810	695	880	765	860	732
w/c Ratio	0,56	0,40	0,56	0,40	0,56	0,40
a/c Ratio	5,24	3,50	5,30	3,55	5,73	3,83
Slump (mm)	90	50	115	70	95	55
Compressive strength (MPa)	37	65	38	65	48	74

Table 2 Calculation of elastic modulus according to the BS 8110 (1985) model and the amended versions of the SABS models

Model	BS 8110 (1985)	SABS 0100 (1992)	SABS 0100 (1992) Mod
Equation used to calculate E	E(GPa) = 20 + 0,2f_{cu}	E(GPa) = K_0 + 0,2f_{cu}	E(GPa) = K_0 + f_{cu}
Variables	E (GPa) = static modulus of elasticity for the age considered f_{cu} (MPa) = 28-day compressive strength K_0 (GPa) = 17 (ferro quartzite); 20 (Jukskei granite); 29 (Eikenhof andesite) α (GPa/MPa) = 0,4 (ferro quartzite); 0,2 (Jukskei granite and Eikenhof andesite)		

- Standards Association of Australia – Australian Standard for Concrete Structures – AS 3600 (1988)
- Comité Euro-International du Béton – Fédération Internationale de la Précontrainte (CEB-FIP) Model Code (1970)
- CEB-FIP Model Code (1978)
- CEB-FIP Model Code (1990)
- International Union of Testing and Research Laboratories for Materials and Structures (RILEM) Model B3 (1995)

The ninth model that has been included is a modified version of the abovementioned SABS 0100 (1992) model. The modifications arose from extensive research by Davis and Alexander (1992). In this paper this model will be referred to as the SABS 0100 (1992) modified model.

The accuracy of these models was assessed by comparing experimental total creep values based on laboratory testing over a period of 168 days, carried out as part of an investigation by Fanourakis (1998), against those predicted at the corresponding ages by the nine models considered. The models were assessed against the strains measured on six different concretes, incorporating combinations of three aggregate types and two w/c ratios as detailed in table 1.

BASIS OF THE MODELS CONSIDERED

The models considered are all empirically based and vary widely in their approach and methodologies. With the exception of 28-day compressive strength, no other results from laboratory tests are required as input. However, certain intrinsic and/or extrinsic variables such as mix proportions, material properties and age of loading are required as input to these models

With the exception of the RILEM Model B3 (1995), all the models considered derive from codes of practice for structural design and express creep strain in terms of the creep coefficient, $\phi(t)$, where:

$$\phi(t) = \frac{\varepsilon_c(t,\tau)}{\varepsilon_{e,\tau}} \tag{1}$$

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. In this form, the creep coefficient is structured to account for the effect of one or more intrinsic and/or extrinsic variables such as concrete stiffness and age at first loading.

The RILEM Model B3 (1995) is, by comparison, more complex than the design code models and takes a more fundamental materials approach to creep prediction. This model enables the calculation of separate compliance functions for the basic creep and drying creep (in excess of the basic creep).

The SABS 0100 (1992) model is based on the British Standard method, BS 8110 (1985), with a small modification arising from research conducted by Davis and Alexander (1992), to the equation used to calculate the elastic modulus (E) of the concrete. The South African code of practice (SABS 0100, 1992) was subsequently renamed SANS 10100 (2000).

The SABS 0100 (1992) modified model is essentially the SABS 0100 (1992) model with a further aggregate specific modification to the calculation of the elastic modulus as well as the application of an aggregate specific relative creep coefficient to modify the calculated total creep. These modifications to the South African models are shown in table 2. By way of comparison, the BS 8110 (1985) model is also shown in table 2.

In the case of the BS 8110 (1985), SABS 0100 (1992) and SABS 0100 (1992) Mod methods, a final (30-year) creep coefficient (ϕ*) is determined from a particular nomograph which accounts for relative humidity, age of loading and the effective thickness of the member. The lowest effective thickness shown in this nomograph is 150 mm, whereas the effective thickness of the specimens tested was 50 mm. A more accurate value of 2,838 for ϕ* was therefore obtained, by non-linear extrapolation from the given values, for an effective thickness of 50 mm.

Furthermore, using a calculated value of the elastic modulus, the SABS 0100 (1992) method allows for the estimation of a final (30-year) creep strain (ε_{cc}) of which 40 %, 60 % and 80 % may be assumed to develop during the first month, 6 months and 30 months of loading, respectively. These values were fitted to a logarithmic curve in order to predict the creep strain at the ages at which measurements were taken on the specimens. This curve takes the form:

$$\varepsilon_c(t-\tau) = \varepsilon_{cc}[0.258 \cdot (\log_{10} t) + 0.0286] \tag{2}$$

Where t is the concrete age and τ is the age of loading, both in days. Hence, $\varepsilon_c(t - \tau)$ is the creep strain since loading.

Details of the parameters selected for each of the models are included in the work of Fanourakis (1998).

LABORATORY TEST PROCEDURE

For each of the concretes listed in table 1, six prisms were prepared, measuring 100 x 100 x 200 mm and cast with the 200 mm dimension vertical. Upon demoulding at approximately 18 hours after casting, the prisms were continuously water cured up to an age of 28 days. The top and bottom ends of three prisms from each concrete were faced on a high-speed facing machine to ensure that these ends were parallel to each other. These faced prisms were used for creep testing while the remaining three prisms were used to monitor the shrinkage of the concretes. A set of Demec targets were glued centrally onto two opposite 200 mm x 100 mm faces. Strain was measured across these targets using a Demec gauge with an accuracy of 16,7 x 10^{-6} per division.

At age 28 days, the faced prisms were placed into creep loading frames as described by Alexander and Ballim (1986) except that the load in the displacement jacks was maintained using nitrogen pressure accumulators. The specimens were kept under an applied load of approximately

Table 3 Measured and predicted elastic moduli and corresponding statistics

Measured	Elastic modulus of concrete (GPa)						T-Test results	
	Q1	Q2	G1	G2	A1	A2	Difference significant?	Level of significance P (%)
	25,8	34,0	27,8	28,9	36,7	40,9		
Predicted								
BS 8110 (1985)	27,40	33,00	27,60	33,00	29,60	34,80	No	45,00
SABS 0100 (1992)	24,40	30,00	27,60	33,00	38,60	43,80	No	67,70
SABS 0100 (1992) Mod	31,80	43,00	27,60	33,00	38,60	43,80	Yes	3,10
ACI 209 (1992) and AS 3600 (1988)	27,70	37,50	28,10	37,50	35,40	45,10	No	9,90
CEB-FIP (1970)	32,50	44,10	33,10	44,10	36,90	47,00	Yes	1,70
CEB-FIP (1978)	29,50	36,10	29,80	36,10	32,10	37,70	No	53,10
CEB-FIP (1990)	31,10	38,00	31,40	38,00	33,80	39,70	No	15,90
RILEM Model B3 (1995)	25,90	35,10	26,40	35,10	29,40	37,50	No	68,20
Average	28,80	37,10	29,00	36,20	34,30	41,20		
Standard deviation	2,91	4,73	2,29	3,75	3,71	4,34		
Variance	8,49	22,33	5,25	14,09	13,76	18,86		

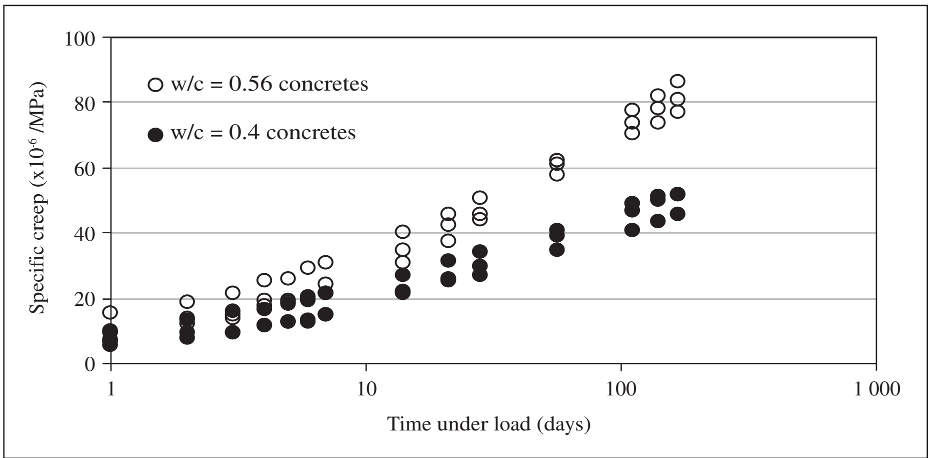

Figure 1 The effect of w/c ratio on specific creep of concrete

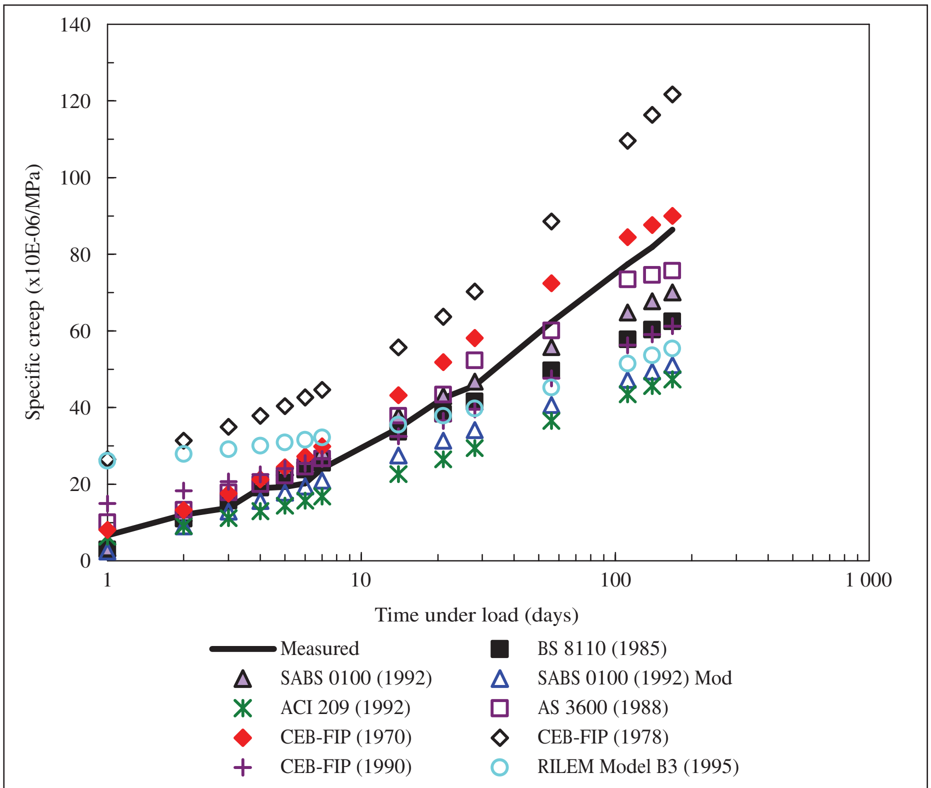

Figure 2 Measured and predicted specific creep for mix Q1 specimens

25 % of the 28-day compressive strength over a period of 168 days. The creep and shrinkage specimens were stored in a room controlled at 22 ± 3 °C and RH of 65 ± 5 %. Assuming an additive relationship between creep and shrinkage, the results of shrinkage measurement were subtracted from the total time-dependent strain of the loaded specimens in order to determine the total creep strain.

For the loaded specimens, elastic strain measurements were taken within 10 minutes of the first application of the loads. These measured values were used to determine the secant elastic modulus of the concretes for comparing with the value estimated by each of the creep models assessed.

RESULTS AND DISCUSSION

Elastic moduli of concrete

All the creep prediction models applied in this investigation include variations of an empirical equation for estimating the elastic modulus of the concrete. Such equations are primarily based on the compressive strength of the concrete at the time of loading. This equation is identical for the ACI 209 (1992) and the AS 3600 (1988) methods. In the case of the RILEM Model B3 (1995), the estimated elastic modulus 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. However, in the case of all the other creep prediction models considered in this paper, the predicted creep strain is directly dependent on the value of the estimated elastic modulus. Hence, the reliability of estimation of the elastic modulus significantly influences the reliability of the prediction of creep.

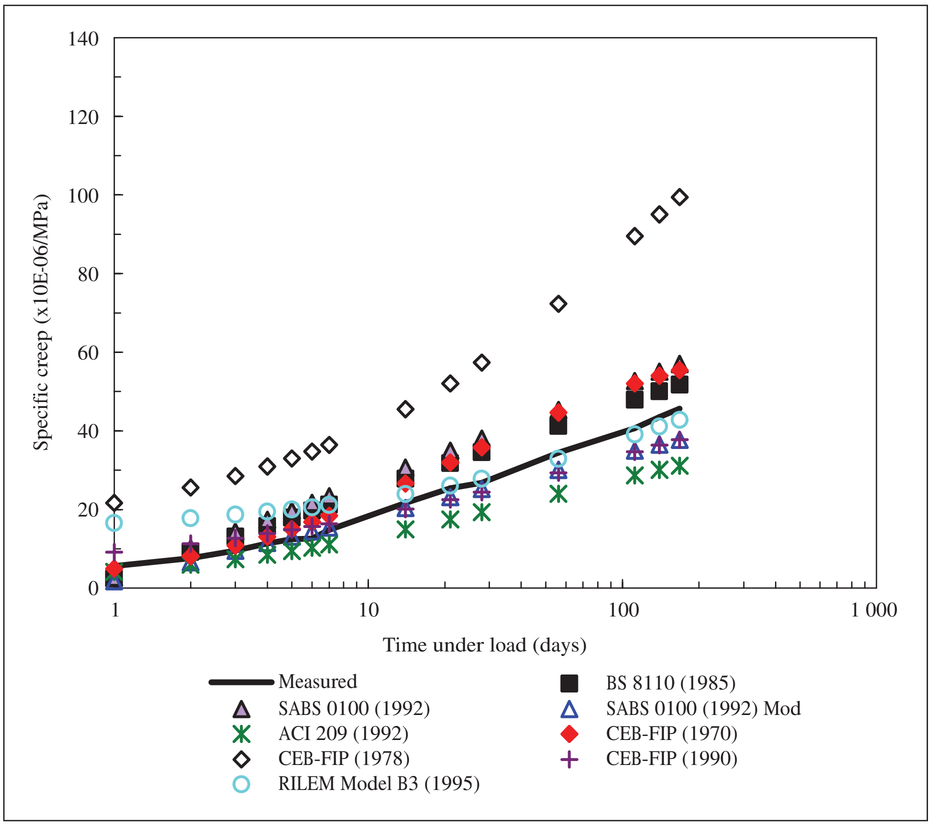

Figure 3 Measured and predicted specific creep for mix Q2 specimens

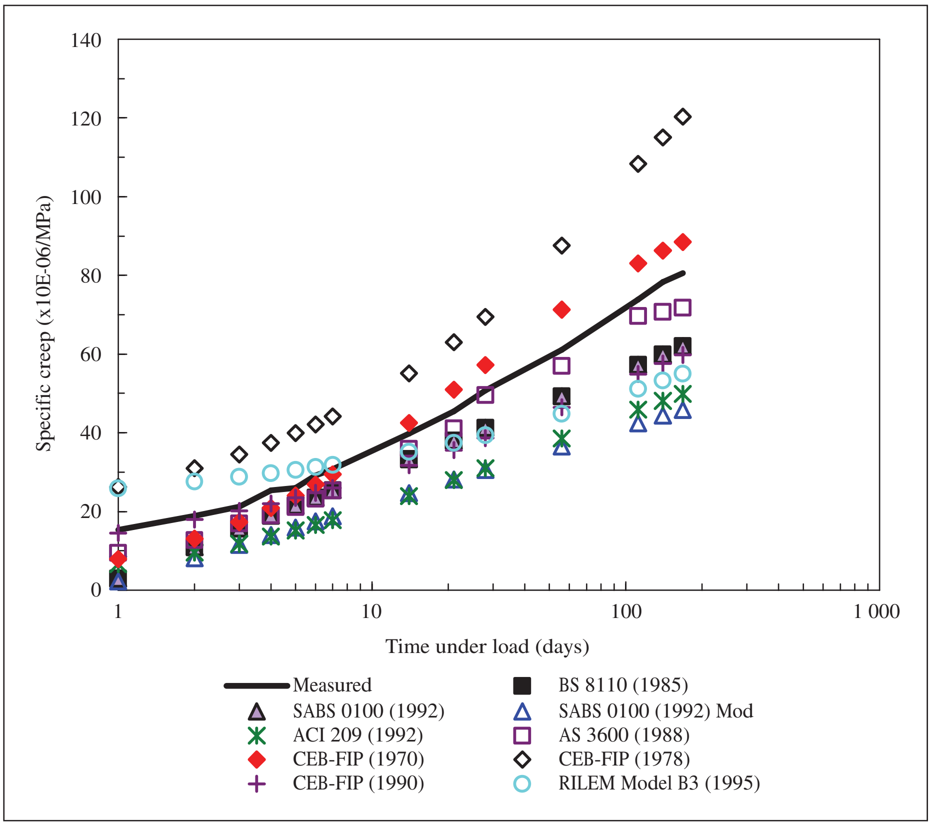

Figure 4 Measured and predicted specific creep for mix G1 specimens

Table 3 shows the estimated elastic moduli for each of the concretes according to the different creep prediction methods together with the average elastic moduli measured at 28 days after casting.

The average, standard deviation and variance shown in the bottom of the table relate to the elastic moduli estimated for the particular concrete by each of the models, while the t-Test results relate to a comparison between the measured and the predicted values for each of the concretes determined by a particular creep prediction method.

The paired (two-tailed) t-Test was applied to paired data values to determine whether the two specimens are likely to have come from the same two underlying populations that have the same mean (Moroney 1984; Cohen 1991; Spiegel 1992). Where applied, the null hypothesis was assumed (ie any observed differences are due to fluctuations within the same population). The 5 % significance level was selected as being appropriate.

The probability calculated is associated with the Student's t-Test. The significance levels established (P) indicate the probability that the magnitudes in the paired readings arose by chance. Therefore, probability values exceeding 5 % indicate that the discrepancies in the paired values are not significant. It should be borne in mind that, in the statistical sense, the result 'not significant' is not so much a complete acceptance of the null hypothesis but rather an outcome of 'significance of difference not established'.

It is evident from table 3 that a relatively larger variance occurred in the values predicted for the lower w/c ratio mixes (Q2, G2 and A2) in comparison with the higher w/c ratio mixes. According to the t-Test results shown in table 3, the discrepancies between the measured and predicted elastic moduli values, for the different mixes, were only significant in the case of the SABS 0100 (1992) Mod method (P = 3,1 %) and the CEB-FIP (1970) method (P = 1,7 %). These significant differences are probably attributable to the general over-estimation of elastic moduli values for each mix in the case of both these methods. The RILEM Model B3 (1995) yields the most accurate predictions (P = 68,2). No trend was established regarding the influence of the included aggregate on the accuracy of the predicted modulus of elasticity.

Total creep

Analytical procedures

The nine creep prediction methods mentioned earlier were used to predict the specific creep at the same ages at which measurements were taken for the concrete of each of the six mixes used in the investigation described in Fanourakis (1998). The predictions were carried out for concrete of the same geometry, temperature and humidity as the laboratory test specimens.

In order to provide a basis for comparing the creep strains of concretes with different strengths and different applied stresses, σ, the results are presented in the form of specific creep (C_c), which is defined as:

$$C_c = \frac{\varepsilon_c(t)}{\sigma} \qquad (3)$$

It should be noted that the high-strength concretes tested (w/c = 0,4) were outside of the allowable range for the use of the Australian model AS 3600 (1988), which is 20 MPa to 50 MPa. This model was therefore only used for the low strength group of concretes.

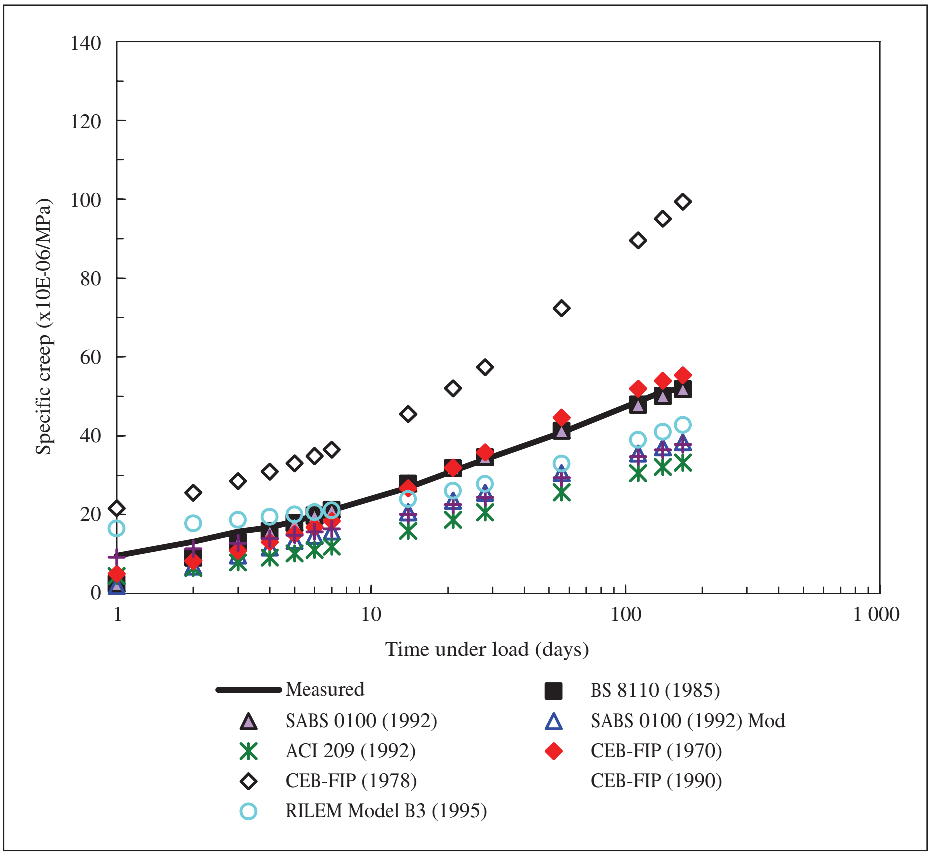

Figure 5 Measured and predicted specific creep for mix G2 specimens

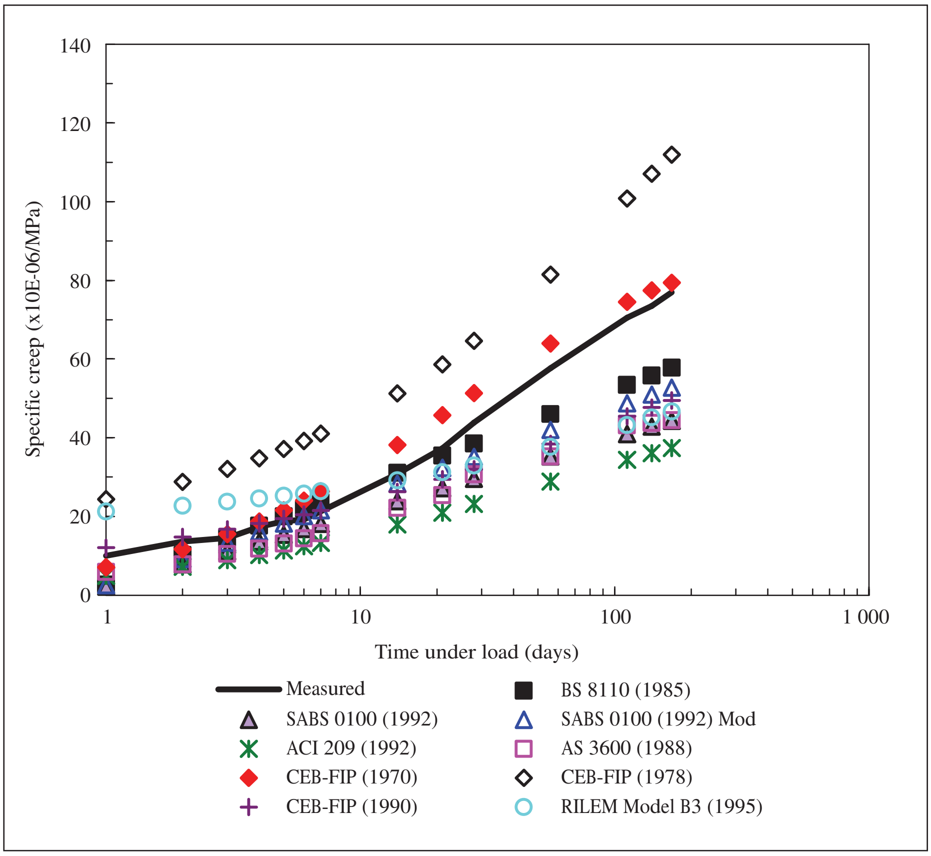

Figure 6 Measured and predicted specific creep for mix A1 specimens

Results

Figure 1 shows a comparison of the measured specific creep results for the concretes, distinguished only by the different w/c ratios. Note that the time axis is plotted on a logarithmic scale to more clearly show the variations at earlier ages. It is clear from figure 1 that for the same ratio of applied stress to compressive strength, concretes with a higher compressive strength show lower creep strains per unit of applied stress. In the case of the concretes tested in this investigation, increasing the w/c ratio from 0,4 to 0,56 caused an approximately 60 % increase in the measured specific creep.

Figures 2 to 7 show comparisons between the measured results for the six mixes (Q1, Q2, G1, G2, A1 and A2) together with the corresponding strains predicted by the different models.

From figures 2 to 7 it is evident that, with the exception of Mix Q2, the CEB-FIP (1970) and, more significantly, the CEB-FIP (1978) models overpredict the creep strain. To varying degrees, the remaining models generally underpredict the creep strains.

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 table 4 below.

These specific creep results indicate that the CEB-FIP (1970) method yielded the most accurate predictions giving the lowest overall coefficient of variation (ω_{all}) of approximately 18 %.

The CEB-FIP (1978) showed the worst accuracy of prediction (ω_{all} = 96,1 %) and this is probably the reason that it was superseded by the 1990 version. Nevertheless, based on the results presented here, the 1990 version does not seem to be an improvement on the 1970 version of the model. The ACI 209 model also showed poor prediction accuracy and, based on the present results, should be used with caution for South African concretes. In general, the methods that significantly over- or under-predicted the creep strains showed increasing deviation from the measured results with increasing time under load (figures 2 to 7). Although applied to the low-strength concretes only, the Australian model showed good prediction accuracy, except for Mix A1.

The RILEM B3 model seems to predict the creep performance of the high strength concretes better that it does that of the low strength concretes. This effect was also noted in a separate investigation by Ballim (2000). Also, the relatively poor overall coefficient of variation for this model (35,6 %) does not seem to justify the significant complexity involved in its application.

Finally, the simplest of all the models, the BS 8110 (1985), yielded the second lowest coefficient of variation (23,6 %) and proved to be more accurate than both its modified South African versions.

With regard to the elastic moduli values predicted by each model, no correlation was found between the accuracy of the specific total creep and the elastic moduli predicted by any of the models. It is interesting to note that the CEB-FIP (1970) which yielded the most accurate specific

Table 4 Coefficients of variation for specific creep

Prediction method	Coefficients of variation (ω_j)						ω_{all}
	Mix Q1	Mix Q2	Mix G1	Mix G2	Mix A1	Mix A2	
BS 8110 (1985)	29,0	27,4	26,5	8,6	26,9	15,5	23,6
SABS 0100 (1992)	20,1	41,4	26,5	8,6	47,9	26,5	31,3
SABS 0100 (1992) modified	45,2	17,3	49,5	31,9	34,4	15,2	34,7
ACI 209 (1992)	52,6	36,3	45,7	45,1	60,8	58,4	50,5
AS 3600 (1988)	12,5	n/a	13,4	n/a	47,2	n/a	29,2
CEB – FIP (1970)	18,1	31,3	15,0	12,3	13,9	9,9	18,1
CEB – FIP (1978)	66,0	148,6	53,9	95,1	65,6	112,8	96,1
CEB – FIP (1990)	32,7	19,8	27,7	31,2	39,6	38,3	32,2
RILEM Model B3 (1995)	45,6	29,3	33,0	21,9	45,3	32,6	35,6

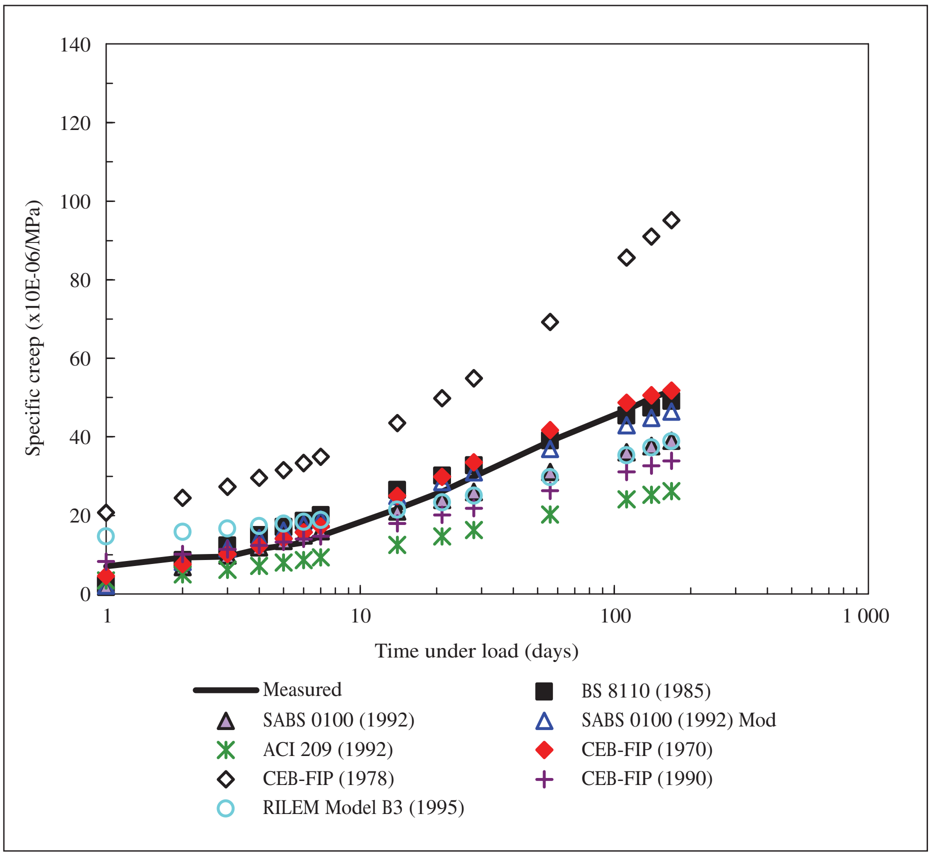

Figure 7 Measured and predicted specific creep for mix A2 specimens

creep predictions (table 4) also yielded the least accurate elastic modulus predictions (table 3). The apparent accuracy of its creep prediction may be a serendipitous result of the inaccuracy of its elastic modulus prediction. Furthermore, in general, the models predicted the elastic modulus more accurately for the low strength mixes and the total creep more accurately for the high strength mixes.

CONCLUSIONS

All the creep prediction methods included in this project consider the value of a predicted elastic modulus of the concrete in calculating predicted creep strain. A comparison of the predicted elastic moduli, determined for each mix by the different creep prediction methods, with the measured elastic moduli of the relevant mixes indicated that the differences were only significant in the case of the SABS 0100 (1992) Mod and the CEB-FIP (1970) methods.

The nine models assessed show significant and wide variation in the magnitude of specific creep predicted over the time period considered. At the extremes, the CEB-FIP (1978) model showed the largest over-prediction, while the ACI 209 model showed the largest under-prediction.

For the range of concretes tested, the CEB-FIP (1970) models gave the most accurate predictions, with overall coefficients of variation of 18 %. The BS 8110 (1985) model, which is the simplest of those included in the investigation, yielded the second most accurate predictions. Furthermore, this model proved to be more accurate than its subsequent variations, the SABS 0100 (1992) and SABS 0100 (1992) Mod, which account for the included aggregate type, and in the case of five of the six mixes underestimated the creep strain.

In its application to the present concretes, both the 1978 and 1990 versions of the CEB-FIP model appear not to be as accurate as the 1970 version of the same model.

The Australian model, AS 3600, gave reasonable predictions for the low strength concretes while the RILEM B3 model showed better prediction accuracy for the high strength concretes tested.

No correlation was found to exist between the accuracy of the elastic modulus and specific total creep as predicted by each of the models.

The accuracy of the predictions did not increase with the complexity of the method applied or with increasing number of variables accounted for in the method.

In view of the above, it is recommended that the BS 8110 (1985) model be used for South African conditions.

Finally, it should be borne in mind that the findings of this investigation pertain to the 168 day period after loading and could be significantly different if the life of the concrete was considered.

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