Materials and Structures/Matériaux et Constructions, Vol. **29**, December 1996, pp 587-593

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TC 107-GCS: GUIDELINES FOR THE FORMULATION OF CREEP AND SHRINKAGE PREDICTION MODELS

Addendum to TC 107-GCS Recommendation: Creep and shrinkage prediction model for analysis and design of concrete structures – Model B3.

RILEM TECHNICAL COMMITTEES

Short form of creep and shrinkage prediction model B3 for structures of medium sensitivity

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FOREWORD

A simple model for the characterisation of concrete creep and shrinkage in design of concrete structures of medium creep and shrinkage sensitivity is proposed. It represents a shortened form of model B3 which was presented as a draft RILEM recommendation and is intended for structures of high sensitivity. The main simplification compared to model B3 comes from the use of the log-double-power law as the basic creep compliance function. The B3 formulae for predicting material parameters in the model are simplified by dropping the dependence of these parameters on the composition of the concrete mix, leaving only dependence on the strength and water content of the concrete mix. The model is justified by statistical comparisons with all the data in the internationally approved RILEM data bank. The differences between the present short-form and model B3 are discussed and limitations of the short-form as compared to model B3 are noted. The model is suitable for design of concrete structures, with the exception of highly creep-sensitive structures for which the full model B3 must be used.

1. APPLICABILITY RANGE

A recent draft RILEM Recommendation [1] presented a prediction model for concrete structures of high sensitivity to the effects of creep and shrinkage, as defined by the categorisation of various types of structures in that recommendation and in Appendix 5. For structures of medium sensitivity, a simplification of model B3, described hereafter, is sufficient. These are structures of sensitivity levels 1 and 2, defined in Appendix 5. The prediction of the material parameters of the present model from strength and composition is restricted to Portland cement concrete with the following parameter ranges:

$$\begin{aligned}&17\text{ MPa} \le \bar{f}_c \le 70\text{ MPa},\\ &160\text{ kg/m}^3 \le c \le 720\text{ kg/m}^3 \quad \text{S.I.}\\ &2500\text{ psi} \le \bar{f}_c \le 10{,}000\text{ psi},\\ &10\text{ lb/ft}^3 \le c \le 45\text{ lbs/ft}^3 \quad \text{American}\end{aligned} \tag{1}$$

$$0.35 \le w/c \le 0.85 \quad 2.5 \le a/c \le 13.5 \tag{2}$$

(the numbers 0.85 and 720 kg/m^3 or 45 lbs/ft^3 are, of course, outside the range of good concretes in today's practice). The formulae are valid for concretes cured for at least one day. Formulae predicting model parameters from the composition of concrete have not been developed for special concretes containing various admixtures, pozzolans, microsilica, and fibers. However, if the model parameters are not predicted from concrete composition and strength but are calibrated by experimental data, the model can be applied even outside the range given by equations (1) and (2), for example, to high-strength concretes, fiber-reinforced concretes, and mortars.

The average compliance function for the cross-section of a long member, representing the sum of the instantaneous deformation, the basic creep and the additional creep due to drying, is expressed as:

$$J(t, t') = q_1 + C_0(t, t') + C_d(t, t', t_0) \tag{3}$$

2. BASIC CREEP

Based on the log-double-power law [3], the basic creep compliance function is given as:

$$C_0(t, t') = q_0 \ln\{1 + \psi[(t')^{-m} + \alpha](t - t')^n\} \quad (4)$$

in which $m = 0.5$, $n = 0.1$, $\alpha = 0.001$, $\psi = 0.3$.

3. MEAN SHRINKAGE AND CREEP OF CROSS SECTION AT DRYING

The initial relative humidity in the pores of concrete is 100%. Subsequent exposure to environment causes a long-term drying process, which causes shrinkage and additional creep.

3.1 Shrinkage

Mean shrinkage strain in the cross section:

$$\varepsilon_{sh}(t, t_0) = -\varepsilon_{sh\infty} k_h S(t) \quad (5)$$

Time dependence:

$$S(t) = \tanh\sqrt{\frac{t - t_0}{\tau_{sh}}} \quad (6)$$

Humidity dependence:

$$k_h = \begin{cases} 1 - h^3 & \text{for } h \geq 0.98 \\ -0.2 & \text{for } h = 1 \text{ (swelling in water)} \\ \text{linear interpolation} & \text{for } 0.98 \leq h \leq 1 \end{cases} \quad (7)$$

Size dependence:

$$\tau_{sh} = 4.9D^2 \text{ (D in cm)} = 32D^2 \text{ (D in inches)} \quad (8)$$

where $D = 2v/s$ = effective cross-section thickness (in inches or cm).

3.2 Additional creep due to drying (drying creep)

$$C_d(t, t', t_0) = q_5 [e^{-3H(t)} - e^{-3H(t')}]^{1/2} \quad \text{for } t' \geq t_0 \quad (9)$$

in which

$$H(t) = 1 - (1 - h)S(t) \quad (10)$$

4. PARAMETER PREDICTION BASED ON STRENGTH AND WATER CONTENT OF CONCRETE MIX

Some formulae that follow are valid only in certain dimensions. These are given both in metric (S.I.) units (MPa, m) and in American units (psi, in.). The units of each dimensional quantity are also specified in the list of notations (Appendix 1).

Basic creep:

$$q_0 = 2408\bar{f}_c^{-0.5};\ q_1 = 0.6 \times 10^6 / E_{28};\ E_{28} = 4734\sqrt{\bar{f}_c} \quad \text{S.I}$$
$$q_0 = 200\bar{f}_c^{-0.5};\ q_1 = 0.6 \times 10^6 / E_{28};\ E_{28} = 57000\sqrt{\bar{f}_c} \quad \text{American} \quad (11)$$

Shrinkage:

$$\varepsilon_{sh\infty} = \alpha_1 \alpha_2 [0.019w^{2.1} (\bar{f}_c)^{-0.28} + 270] \text{ (in } 10^{-6}) \quad \text{S.I.}$$
$$\varepsilon_{sh\infty} = \alpha_1 \alpha_2 [26w^{2.1} (\bar{f}_c)^{-0.28} + 270] \text{ (in } 10^{-6}) \quad \text{American} \quad (12)$$

where

$$\alpha_1 = \begin{cases} 1.0 & \text{for type I cement;} \\ 0.85 & \text{for type II cement;} \\ 1.1 & \text{for type III cement.} \end{cases} \quad (13)$$

and

$$\alpha_2 = \begin{cases} 0.75 & \text{for steam-cured concrete;} \\ 1.0 & \text{for concrete cured in water or 100\% relative humidity;} \\ 1.2 & \text{for concrete sealed during curing.} \end{cases} \quad (14)$$

Creep at drying (happens to be the same in both S.I. and American units)

$$q_5 = 6000(\bar{f}_c)^{-1} \quad (15)$$

Fig. 1 shows creep and shrinkage curves for typical parameter values. The scatter plots of all the data in the data bank compared to the predicted values are shown in Fig. 2. Fig. 3 shows comparisons of predictions of the model with some typical test data from the literature (for reference to these data see [2]).

5. STATISTICS OF ERRORS COMPARED TO TEST DATA

The model is statistically evaluated in the same manner as previously described for model B3 [2], [1]. The coefficients of variation of errors in comparison to all the data from the RILEM data bank are tabulated in Tables 1-3. Fig. 2 shows the scatter plots comparing the model predictions to the measured data. These statistics and scatter plots are slightly worse than those for the full model B3, but are significantly better than those for the previous ACI 209 model (Chapter 2 in ACI R-92 [4]). The statistics are also better than those for the new CEB-FIP model [5] and the GZ model proposed to subcommittee 4 of ACI 209 [6].

6. COMPARISON WITH MODEL B3

The B3 model reported in ACI 209-R96 is more detailed and rational than its present short form, which is more suited for simplified calculations of creep and shrinkage effects in concrete structures. Specifically, the following points must be mentioned when considering the relative merits of the two models.

1. The compliance function for basic creep in model B3 has been derived from the solidification theory. It gives

a simple formula for the time rate of compliance, which is convenient for use in step-by-step computer analysis of structures. The expression for the compliance function itself is more complex for the B3 model than the log-double-power law used in the present short form.

2. The log-double-power law exhibits the phenomenon of divergence of creep curves and thus, in principle, violates one of the guidelines [7] by RILEM TC 107 for creep and shrinkage prediction models. However, the violation is never too pronounced and occurs only for short time periods. The violation may cause the phenomenon of stress reversal when creep recovery calculations are performed based on this formula using the principle of superposition. It may also cause long-time stress relaxation of concrete stressed at low age to reach into negative values. The B3 model, based on the solidification theory, is free from such problematic predictions. The problem is nevertheless not serious for normal applications.

3. The shrinkage formulation in the present short form, though essentially similar to the B3 model, does not include the influence of curing duration and specimen size on the final shrinkage.

4. A look at the values of coefficients of variation and the scatter-plots of measured versus calculated values of creep and shrinkage deformations shows that the B3 model is overall distinctly more accurate than the present short form. The predictions of the present short form are better than the 1990 CEB-FIP model [5] for basic creep and shrinkage and comparable to it for creep at drying.

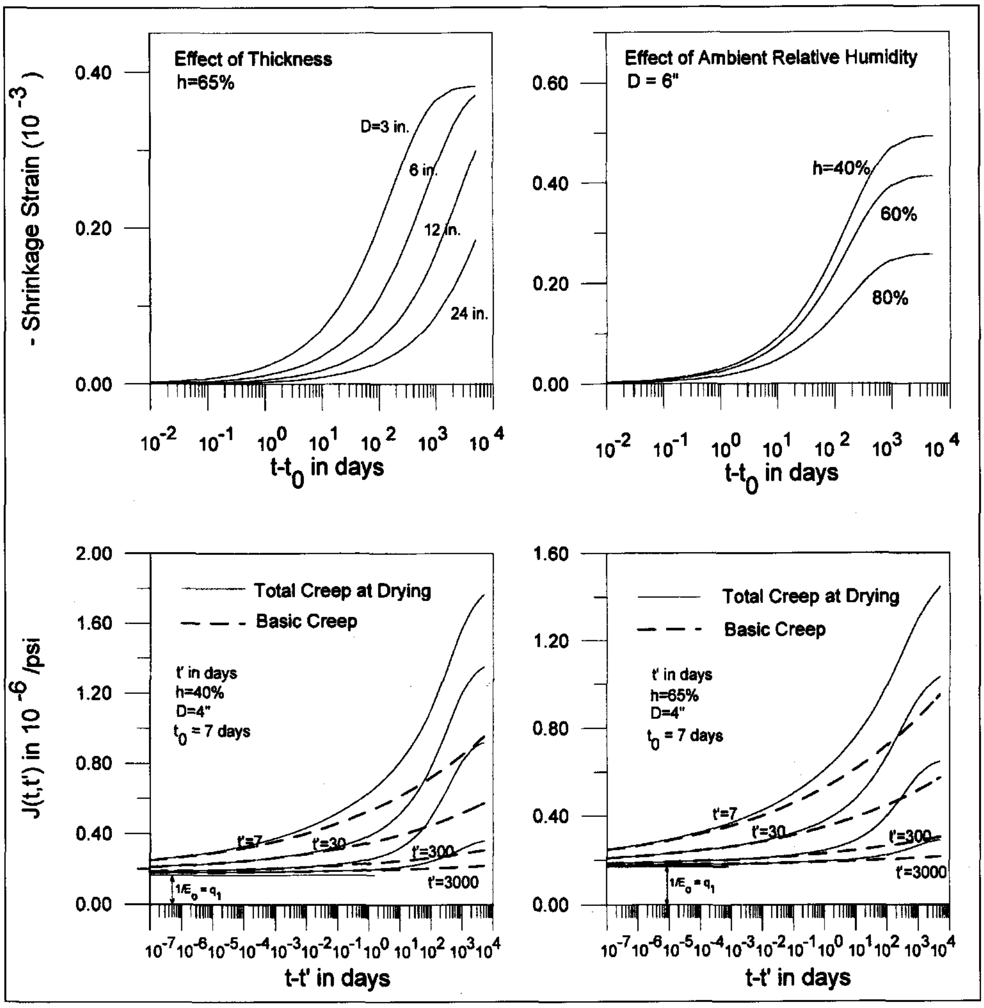

Fig. 1 – Typical shrinkage and creep curves given by the Model B3 (short form).

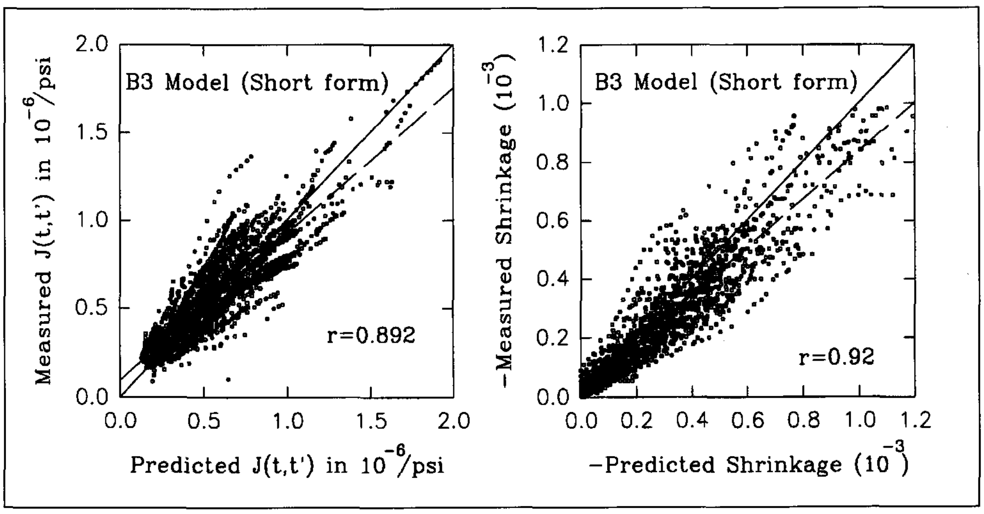

Fig. 2 – Scatter plots of measured versus predicted values of creep and shrinkage (dashed lines are regression lines).

APPENDIX 1 - NOTATION

All notations introduced in [1] are retained. They are as follows:

t = time, representing the age of concrete, in days;

t' = age at loading, in days;

t_0 = age when drying begins, in days (only $t_0 \leq t'$ is considered);

$J(t, t')$ = compliance function = strain (creep plus elastic) at time t caused by a unit uniaxial constant stress applied at age t' (always given in 10^{-6}/psi, the S.I. version of the formulae gives $J(t, t')$ in 10^{-6}/MPa, 1 psi = 6895 Pa);

$C_0(t, t')$ = compliance function for basic creep only;

$C_d(t, t', t_0)$ = compliance function for additional creep due to drying;

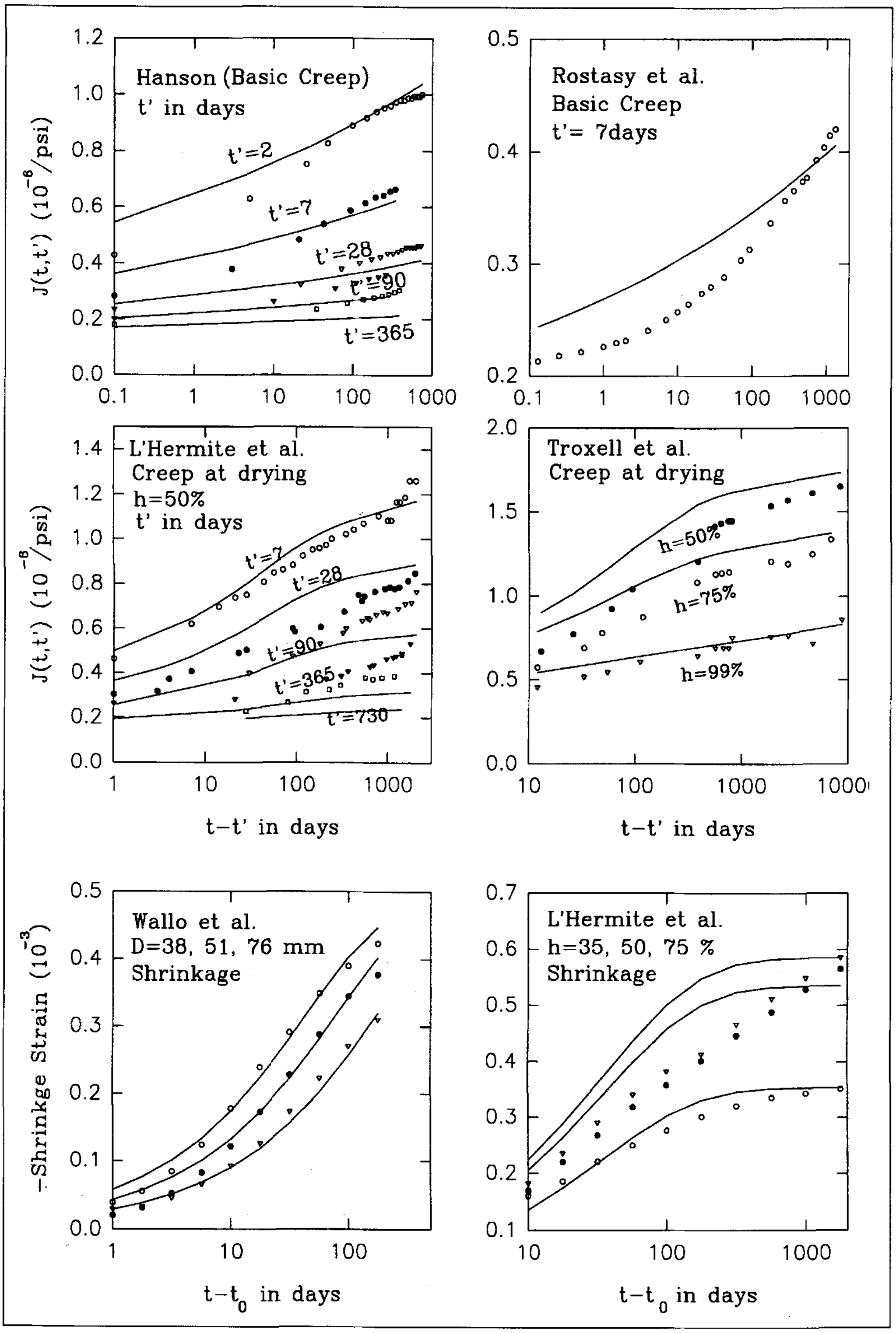

Fig. 3 - Comparison of model predictions to some typical test data from the literature.

ε_{sh}, $\varepsilon_{sh\infty}$ = shrinkage strain and ultimate (final) shrinkage strain; $\varepsilon_{sh\infty} \geq 0$ but ε_{sh} is considered negative (except for swelling, for which the sign is positive); always given in 10^{-6};

h = relative humidity of the environment (expressed as a decimal number, not as a percentage) $0 \leq h \leq 1$;

H = spatial average of pore relative humidity within the cross section, $0 \leq H \leq 1$;

$S(t)$ = time function for shrinkage;

τ_{sh} = shrinkage half-time in days;

$D = 2v/s$ = effective cross section thickness in inches (in mm for the S.I. version, 1 inch = 25.4 mm);

v/s = volume-to-surface ration in inches or cm;

c = cement content of concrete in lb/ft^3 (in kg/m^3 for the S.I. version, 1 lb/ft^3 = 16.03 kg/m^3);

w/c = water-cement ratio, by weight;

$w = (w/c)c$ = water content of concrete mix in lb/ft^3 (in kg/m^3 for the S.I. version);

a/c = aggregate-cement ratio, by weight;

$\bar{f}_c$ = mean 28-day standard cylinder compression strength in psi (in MPa for the S.I. version, 1 psi = 6895 MPa) (if only design strength f'_c is known, then $\bar{f}_c = f'_c + 1200$ psi);

Table 1 - Coefficient of variations of errors (expressed as a percentage) of the basic creep predictions

Model	B3S
Test data	$\bar{\omega}$
1. Keeton	22.5
2. Kommendant *et al.*	18.3
3. L'Hermite *et al.*	48.6
4. Rostasy *et al.*	16.4
5. Troxemm *et al.*	9.8
6. York *et al.*	11.0
7. McDonald	8.4
8. Maity and Meyers	13.4
9. Mossiossian and Gamble	20.0
10.Hansen and Harboe *et al.* (Ross Dam)	18.2
11. Browne *et al.* (Wylfa vessel)	51.8
12. Hansen and Harboe *et al.* (Shasta Dam)	22.2
13. Brooks and Wainwright	15.4
14. Pirtz (Dworshak Dam)	9.6
15. Hansen and Harboe *et al.* (Canyon derry Dam)	54.8
16. Russel and Burg (Water Tower Place)	30.2
17. Hanson	15.8
$\bar{\omega}_{all}$	26.9

Table 2 - Coefficient of variations of errors (expressed as a percentage) of the shrinkage predictions

Model	B3S
Test data	$\bar{\omega}$
1. Hummel *et al.*	32.4
2. Rüsch *et al.* (1)	35.3
3. Wesche *et al.*	46.9
4. Rüsch *et al.* (2)	33.3
5. Wischers and Dahms	25.0
6. Hansen and Mattock	21.1
7. Keeton	47.1
8. Troxell *et al.*	69.6
9. Aschl and Stökl	31.2
10. Stökl	36.5
11. L'Hermite *et al.*	71.4
12. York *et al.*	57.5
13. Hilsdorf	15.8
14. L'Hermite and Mamillan	36.0
15. Wallo *et al.*	26.8
16. Lambotte and Mommens	44.8
17. Weigler and Karl	37.6
18. Wittmann *et al.*	42.7
19. Ngab et al.	25.9
20. McDonald	23.3
21. Russell and Burg (Water Tower Place)	42.3
$\bar{\omega}_{all}$	40.8

q_1, q_0, q_5 = empirical material constitutive parameters given by formulae based on concrete strength;
$\phi(t, t')$ = creep coefficient;
k_h = humidity correction factor for final shrinkage;
k_t = parameter used in calculation of τ_{sh}.

Table 3 - Coefficient of variations of errors (expressed as a percentage) of the predictions of creep at drying

Model	B3S
Test data	$\bar{\omega}$
1. Hansen and Mattock	34.9
2. Keeton	4.4
3. Troxell *et al.*	14.7
4. L'Hermite *et al.*	27.2
5. Rostasy *et al.*	28.7
6. York *et al.*	34.1
7. McDonald	30.2
8. Hummel	28.9
9. L'Hermite and Mamillan	27.5
10. Mossiossian and Gamble	17.0
11. Maity and Meyers	71.3
12. Russell and Burg (Water Tower Place	29.0
13. Weil	23.1
14. Hilsdorf *et al.*	23.3
15. Wischers and Dahms	25.9
16. Wesche *et al.*	34.9
17. Rüsch *et al.*	17.9
$\bar{\omega}_{all}$	26.9

APPENDIX 2 - HYPOTHESES AND EXPLANATIONS

The present prediction model is restricted to the service stress range for which creep is assumed to be linearly dependent on stress. This means that, for constant stress s applied at age t',

$$\varepsilon(t) = J(t, t')\sigma + \varepsilon_{sh}(t) + \alpha\Delta T(t) \tag{16}$$

in which σ = uniaxial stress, ε = strain, $\Delta T(t)$ = temperature change from reference temperature at time t, α = thermal expansion coefficient. When stresses vary in time, the corresponding strain can be obtained from (3) according to the principle of superposition [8, 9]. Simplified design calculations can be performed according to the age-adjusted effective modulus method, which allows quasi-elastic analysis [8, 10] of the structure.

The compliance function, giving the strain per unit stress, may further be decomposed as given by equation (3), in which q_1 instantaneous strain due to unit stress, $C_0(t, t')$ = compliance function for basic creep (creep at constant moisture content), and $C_d(t, t', t_0)$ = additional compliance function due to simultaneous drying. For generalisation to multiaxial creep, the creep Poisson ratio may be assumed to be constant and equal to the instantaneous Poisson ration ν = 0.18. (Tensile microcracking can cause the apparent Poisson ratio to be much smaller, but this is properly taken into account by a model for cracking.)

The instantaneous strain, same as in previous models [11, 12], may be written as $q_1 = 1/E_0$ where E_0 = asymptotic modulus. The use of E_0 instead of the static elastic modulus E is convenient, because concrete exhibits pronounced creep even for very short load durations (even shorter than 10^{-4} s). E_0 should not be regarded as the real elastic modulus but merely as a convenient parameter that can be considered age-independent. As a rough estimate, $E_0 \approx 1.5E$. The value of the usual static elastic modulus E normally obtained in tests and used in structural analysis corresponds approximately to

$$E(t') = 1/J(t' + \Delta, t') \tag{17}$$

in which the stress duration $\Delta = 0.01$ day gives values approximately agreeing with ACI formula, $E = 57{,}000 \sqrt{\bar{f}_c}$ in psi (or $E = 4734 \sqrt{\bar{f}_c}$ in MPa). The advantage of defining q_1 by extrapolation to extremely fast loading is that q_1 (or E_0) can be considered as age independent and equation (17) also gives the age dependence of the elastic modulus. The value $\Delta = 10^{-7}$ day gives approximately correct values of the dynamic modulus of concrete and its age dependence. The meaning of the value of $q_1 = 1/E_0$ is explained in Fig. 1, which also shows the typical curves of basic creep, shrinkage and drying creep according to the present model.

The creep coefficient, which represents the most convenient way to introduce creep into structural analysis, should be calculated from the compliance function, *i.e.*,

$$\phi(t, t') = E(t')J(t, t') - 1 \tag{18}$$

Note that for structural analysis it is not important which value of Δ corresponds to $E(t')$ in equation (18), and not even whether some other definition of E is used in equation (18). One can use the ACI formula, $E = 57000 \sqrt{\bar{f}_c}$ in psi (or $E = 4734 \sqrt{\bar{f}_c}$ in MPa), or equation (17) for any value of $\Delta \leq 0.1$. For the results of structural analysis of creep and shrinkage (for $t - t' \leq 1$ day), the only important aspect is that E and ϕ together must give the correct total compliance $J(t, t') = [1 + \phi(t, t')]/E(t')$, as defined by model B3.

Note that if a prediction model specified ϕ instead of J, there would be danger of combining ϕ with some incompatible value of E, which would give wrong J values. What matters for structural calculations is only the values of J, and not the values of ϕ and E that yield J. Care in this regard must also be taken when updating the model parameters from test data for which only the values of ϕ were reported. $J(t, t')$ cannot be calculated from such data using a definition of E, for example, $E = 57000 \sqrt{\bar{f}_c}$ in psi, which does not give values compatible with these ϕ-values and gives $J(t, t')$ disagreeing with equation (18). Conversions of such data from ϕ to J-values must be based on short-time strains measured on the creep specimens themselves; otherwise, such data cannot be used.

The relative humidity in the pores of concrete is initially 100%. In the absence of moisture exchange (as in sealed concretes), a subsequent decrease of pore humidity, called self-desiccation, is caused by hydration, but in normal concretes this decrease is small (to about 96%-98%). Exposure to environment causes a long-term drying process (described by the solutions of the diffusion equation), which causes shrinkage and additional creep. This means that the normal strain $J(t, t')\sigma$, representing the sum of the elastic and creep strains, is measured by subtracting the deformations of a loaded specimen and a load-free companion. For shear creep this is not necessary, because shrinkage is strictly a volume change.

In the absence of drying there is another kind of shrinkage, called autogeneous shrinkage, which is caused by the chemical reactions of hydration. This shrinkage usually is small for normal concretes and can be neglected (but not for high-strength concretes). It does not occur if the relative humidity in the pores drops significantly below 100%. Further shrinkage (or expansion) may be caused by various chemical reactions, for example carbonation. However, in good concretes, carbonation occurs only in a surface layer a few millimeters thick and can be neglected for normal structures. For concrete submerged in water ($h = 100\%$), there is positive ε_{sh}, that is, swelling, which is approximately predicted by the present model upon substituting $h = 100\%$.

APPENDIX 3 – PARAMETER UNCERTAINTIES TO BE CONSIDERED IN DESIGN

The parameters of any creep and shrinkage model must be considered as statistical variables. The preceding formulae predicting the creep and shrinkage parameters from concrete composition and strength give the mean value of $J(t, t')$ and ε_{sh}. To take into account statistical uncertainties, the parameters q_1, q_0, q_5, $\varepsilon_{sh\infty}$ should be replaced by the values

$$\psi_1 q_1,\ \psi_1 q_0,\ \psi_1 q_5,\ \psi_2 \varepsilon_{sh\infty} \tag{19}$$

Here ψ_1 and ψ_2 are uncertainty factors for creep and shrinkage, which may be assumed to follow roughly the normal (Gaussian) distribution with mean value 1. According to the statistical analysis of the data in the data bank, the following coefficients of variation of these uncertainty factors should be considered in design:

$$\begin{aligned} \omega(\psi_1) &= 31\% \quad \text{for creep, with or without drying} \\ \omega(\psi_2) &= 41\% \quad \text{for shrinkage} \end{aligned} \tag{20}$$

Other input parameters of the model are also statistical variables. At the least, the designer should consider the statistical variations of environmental humidity h and of strength $\bar{f}_c$. This can be done by replacing them with $\psi_3 h$ and $\psi_4 \bar{f}_c$, where ψ_3 and ψ_4 are uncertainty factors having a normal distribution with mean 1. In the absence of other information, the following coefficients of variation may be considered for these uncertainty factors [13]:

$$\begin{aligned} \omega(\psi_3) &\approx 20\% \quad \text{for } h \rightarrow \psi_3 h \\ \omega(\psi_4) &\approx 15\% \quad \text{for } \bar{f}_c \rightarrow \psi_4 \bar{f}_c \end{aligned} \tag{21}$$

Factor ψ_3 is statistically independent of ψ_1, ψ_2 and ψ_4, and all the factors may be assumed to be mutually statistically independent, as an approximation.

APPENDIX 4 – PREDICTION IMPROVEMENT BASED ON SHORT-TIME TESTS

The considerable uncertainty in the prediction of creep and shrinkage of concrete, reflected in the values of the coefficients of variation in equation (20), is caused mainly by the effect of the composition and strength of concrete. This effect is very complicated and not sufficiently understood in quantitative terms. At present, the only way to reduce the uncertainty is to conduct short-time tests and use them to update the values of the material parameters in the model. This approach is particularly simple for creep but is more difficult for shrinkage [2]. A method to improve the prediction, based on short-time shrinkage tests coupled with measurements of water (weight) loss, is described in [2]. This method can be applied to the present short form.

APPENDIX 5 - LEVELS OF CREEP SENSITIVITY OF STRUCTURES AND TYPE OF ANALYSIS REQUIRED

Accurate and laborious analysis of creep and shrinkage is necessary for some types of structures, but not for others. It depends on the sensitivity of the structure. Although more precise studies are needed, the following approximate classification of sensitivity levels of structures can be made on the basis of general experience.

Level 1. Reinforced concrete beams, frames and slabs with spans under 20 m (65 ft) and heights of up to 30 m (100 ft), plain concrete footings, retaining walls.

Level 2. Prestressed beams or slabs of spans up to 20 m (65 ft), high-rise building frames up to 100 m (325 ft) high.

Level 3. Medium-span box girder, cable-stayed or arch bridges with spans of up to 80 m (260 ft), ordinary tanks, silos, pavements.

Level 4. Long-span prestressed box girder, cable-stayed or arch bridges; large bridges built sequentially in stages by joining parts; large gravity, arch or buttress dams; cooling towers; large roof shells; very tall buildings.

Level 5. Record span bridges, nuclear containments and vessels, large offshore structures, large cooling towers, record-span thin roof shells, record-span slender arch bridges.

As concerns the type of model and analysis, the following recommendations can be made:

1. The use of a model as realistic and sophisticated as B3: recommended but not strictly required for level 3; mandatory for levels 4 and 5. For levels 1 and 2, the present model suffices. Such a model should always be used for structures analysed by sophisticated computer methods, including two or three dimensional finite elements (because it makes no sense to input inaccurate material properties into a very accurate computer program for the analysis of stresses and deflections).

2. Method of structural creep analysis: the age-adjusted effective modulus method is recommended for levels 3 and 4. The effective modulus method suffices for level 2. For level 1, creep and shrinkage analysis of the structure is not needed, but a crude empirically-based estimate is desirable. Level 5 requires the most realistic and accurate analysis possible, typically a step-by-step computer solution based on a constitutive law, coupled with the solution of the differential equations for drying and heat conduction.

3. Statistical analysis with estimation of 95% confidence limits; (a) mandatory for level 5; (b) highly recommended for level 4; (c) for lower levels desirable but not necessary; however, the confidence limits for any response X (such as deflection or stress) should be considered, being estimated as $\bar{X} \times (1 \pm 1.96\omega)$, where $\bar{X}$ = mean estimate of X and ω is taken the same as in equation (20).

4. Analysis of temperature effects and effects of cycling of loads and environment: must be detailed for level 5 and approximate for level 4. It is not necessary, though advisable, for level 3, and can be ignored for levels 1 and 2 (except for heat of hydration effects).

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Note: A potential user of model B3 should note the Errata mentionned in reference [1].