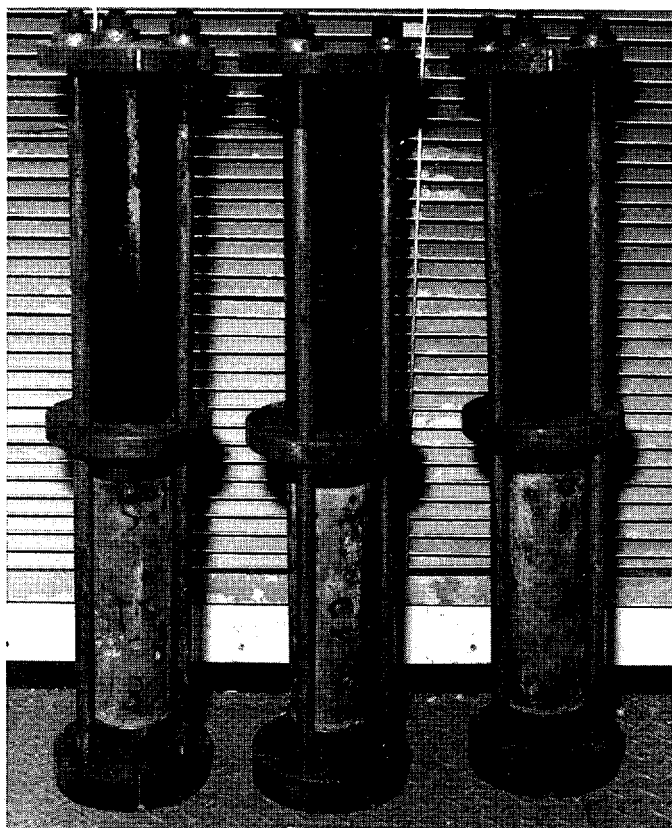


CREEP AND SHRINKAGE OF CONCRETE: EFFECT OF MATERIALS AND ENVIRONMENT



Marwan A. Daye
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Editors



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PREFACE

This special publication is the second publication in the 1990's to cover the topics of Creep and Shrinkage. A previous volume titled "Creep, Shrinkage, and Temperature Change and Their Effects on Concrete Structures—Computer Analysis" was published by ACI in 1991 as SP-129. The main theme of this volume is "The Effect of Concrete Constituents and Environment on Creep and Shrinkage." The 1989 ACI Fall Convention was held in November of 1989 in San Diego, California, and the technical sessions of this topic, sponsored by ACI Committee 209, were held in three parts on November 2 and 3. Six (6) papers with authors from the United States, England, Canada and Germany were presented, and the papers were later submitted and approved, after review, for this special publication. Other papers were also presented but not in a ready-to-be-published form, and so they are not included in this volume.

The current ACI 209 prediction models for creep and shrinkage have been developed for over twenty years. Over the years, new prediction models with state-of-the-art technology, material with more and more popular admixture and easy-to-be-applied equations have been urged by the research and engineering community. CEB-FIP model code 1990 took the first step to include new prediction models for creep and shrinkage of concrete on the basis of a computerized data bank. ACI Committee 209 has, for years, studied the new models which are close to being published in a brand new form. The CEB-FIP models presented by H.S. Muller were adopted by the European Community for readers' interest or application.

As stated before, in recent years, there has been a considerable increase in the use of admixtures and cement replacement materials. The paper presented by Brooks and Neville, from England, reviews this topic and discusses the influence of admixtures and cement replacement materials on creep and shrinkage. The study done by Soroushian, Nagi, and Mustata, assesses the effect of carbon fiber reinforcement on drying strains in cementitious matrices. Marzouk, from Canada, discusses the creep effect of high strength concrete which contains fly ash and silica fume as a partial replacement for cement. Hirata, Smith, and Hammons present another important item — finding the interaction of thermal stress and concrete creep based on the experimental results of two concrete mixtures with high proportions of fly ash in portland cement.

Another topic relates to the pavement and describes the utilization

of compacted cement-phosphogypsum mixtures. Ling, Lin, and Chang present their findings on the shrinkage properties of these different admixtures.

With this variety of topics about the effect of concrete constituents and environment on creep and shrinkage, this volume should provide valuable information to the readers.

C.C. Fu and M.A. Daye
Editors
April, 1992

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CREEP AND SHRINKAGE OF CONCRETE

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New Prediction Models for Creep and Shrinkage of Concrete

by H.S. Muller

Synopsis: The Comité Euro-International du Béton (CEB) has prepared a new model code for the design and analysis of concrete structures (CEB-FIP Model Code 1990) which includes new prediction models for creep and shrinkage of concrete. These models have been derived and optimized on the basis of a computerized data bank. For the prediction of shrinkage a diffusion theory type model has been chosen. The prediction of creep is based on a simple product type approach. Though the new creep model resembles some of the features of the model presented by ACI 209, various basic improvements could be achieved. The coefficients of variation for shrinkage and creep have been found to be approximately 33% and 20%, respectively. The developed prediction models, both for creep and shrinkage represent a reasonable compromise of accuracy and simplicity. They meet the requirements for presentation in a code. In this paper both models are presented and some comparisons with test data are shown.

Keywords: Coefficient of variation; creep properties; models; modulus of elasticity; shrinkage; stresses; temperature

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GENERAL

The analytical relations given for creep and shrinkage in chapter 2.1 of CEB-FIP Model Code 1990 (CEB MC 90; CEB = Euro-International Committee for Concrete; FIP = International Federation for Prestressing) [1] are based primarily on the work of the former CEB General Task Group 9 (GTG 9) "Evaluation of the time dependent behavior of concrete" [2]. The prediction methods have been developed on the basis of a data bank on laboratory test results on structural concrete at normal ambient temperatures. Only such parameters which are known to the designer in practically all cases have been taken into account in the prediction methods. To avoid any confusion, all equations have been given in a non-dimensional presentation.

The models have been developed primarily to predict the mean cross-section behavior of concrete, i.e. the mean properties of a given cross-section are estimated considering the average relative humidity and member size. Local stress and moisture states as well as local cracking cannot be taken into account with such a model. As a crude approximation, however, such models may also be used as a basis for a FE point by point analysis if the relations for very thin sections are properly calibrated and other relations given in chapter 2.1 of CEB MC 90 [1] are taken into account such as the data on fracture properties and the data on moisture movement.

CREEP

Background and Range of Validity

In modeling the creep behavior of concrete as a linear code-type approach two types of formulations have been used in the past: The summation and the product models. They differ in their mathematical approach. Some aspects will be briefly summarized in the following; details may be found in [2], [3], [4].

The product model (also called: aging creep model) is characterized by the feature that creep is calculated from the product of a function describing the effect of age at loading and a function describing the effect of duration of loading. The prediction methods given in various codes and recommendations, e.g.

in [5], [6] and [7], and also the BP Model [8] belong to the group of product models.

The specific feature of the summation model (also called: rate of flow model or improved Dischinger) is the separation of creep into delayed elasticity and flow. The formulation of the flow term reveals an additional characteristic of the summation model, i.e. the effect of age at loading and the time development are expressed by one unique time function. This type of creep prediction model underlies the approaches given in the German Standard DIN 4227 [9] (DIN = German Institute for Standardization) and in principle also the method given in CEB-FIP Model Code 1978 [10].

The differences between the two types of linear creep models become particularly evident when the models are used to predict the effect of variable stresses or strains in combination with the principle of superposition. However, even for the prediction of creep under constant stress, some systematic differences may be observed. Fig. 1 summarizes the basic differences of the models concerning their accuracy of prediction for various load histories. It should be emphasized that this comparison considers the models itself in view of their mathematical approach and evaluates their aptness to predict various effects. Nevertheless, the conclusions which may be drawn from this comparison are also valid for prediction methods as given in recommendations, which are developed on the basis of these models.

It is obvious that neither approach gives correct answers in all cases. This is also true for improved product and summation models as they have been presented e.g. in [8], [4] and [2]. The major reason for the weaknesses of the models is that creep is in fact a nonlinear phenomenon which can only be modeled correctly by means of a nonlinear approach. In addition, creep is strongly interrelated with shrinkage and elastic strain. Where linear prediction models are under consideration, a summation model as presented e.g. in [2] and extended in [11] seems to be the best compromise. However, there are loading cases where such an approach may still be erroneous. Thus, the controversy about the "best" linear creep law will continue.

In CEB MC 90 a product type formulation has been chosen because it can be presented and dealt with in a simpler manner than a summation formulation [2]. In addition, the designer may adopt practical approaches, i.e. approximate constitutive equations [1] to calculate the effects of variable stresses or strains, e.g. the age-adjusted-effective-modulus method.

Unless special provisions are given the model is valid for ordinary structural concrete having a compressive strength at the age of 28 days, f_{cm} , ranging from $20 \text{ N/mm}^2 < f_{cm} < 90 \text{ N/mm}^2$ subjected to a compressive stress $\sigma_c < 0.4 f_c(t_0)$ at an age at loading t_0 and exposed to mean relative humidities in the range of 40 % to 100 % at mean temperatures from 5°C to 30°C . Some

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extensions of the model have been developed to allow an estimate of the effects of temperature and high stresses upon creep [1]. Details on the applicability of the relations presented are given in [2].

Basic Equations

The total load dependent strain at time t , $\epsilon_{cs}(t, t_0)$, of a concrete member uniaxially loaded at time t_0 with a constant stress $\sigma_c(t_0)$ is subdivided as follows:

$$\epsilon_{cs}(t, t_0) = \epsilon_{ci}(t_0) + \epsilon_{cc}(t, t_0) \quad (1)$$

where $\epsilon_{ci}(t_0)$ is the initial elastic strain at loading and $\epsilon_{cc}(t, t_0)$ represents the creep strain at time $t > t_0$. Both strain components may also be expressed by means of the tangent moduli of elasticity $E_c(t_0)$ and E_c , and the creep coefficient $\phi(t, t_0)$, respectively:

$$\epsilon_{ci}(t_0) = \frac{\sigma_c(t_0)}{E_c(t_0)} \quad (2)$$

$$\epsilon_{cc}(t, t_0) = \frac{\sigma_c(t_0)}{E_c} \cdot \phi(t, t_0) \quad (3)$$

In eqs. 2 and 3, $E_c(t_0)$ represents the tangent modulus of elasticity at a concrete age t_0 and $E_c = E_c(t_0 = 28 \text{ days})$. With help of eqs. 2 and 3, eq. 1 may be written as:

$$\epsilon_{cs}(t, t_0) = \sigma_c(t_0) \cdot \left[\frac{1}{E_c(t_0)} + \frac{\phi(t, t_0)}{E_c} \right] \quad (4)$$

$$= \sigma_c(t_0) \cdot J(t, t_0) \quad (5)$$

where $J(t, t_0)$ is the creep function or the creep compliance, representing the total stress dependent strain per unit stress.

Prediction of the Tangent Modulus of Elasticity

Values of the tangent modulus of elasticity for normal weight concrete, E_c , can be estimated from eq. 6:

$$E_c = E_{co} \cdot (f_{cm}/f_{cmo})^{1/3} \quad (6)$$

where f_{cm} is the mean compressive strength of concrete cylinders (in $[N/mm^2]$), 150 mm in diameter and 300 mm in height stored in water at $20 \pm 2^\circ C$, and tested at the age of 28 days in accordance with ISO 1920, ISO 2736/2 and ISO 4012 (ISO = International Organization for Standardization); $E_{co} = 21500 N/mm^2$ and $f_{cmo} = 10 N/mm^2$.

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Eq. 6 is valid for concretes made of quartzitic aggregates. For concrete made of basalt, dense limestone, limestone or sandstone the modulus of elasticity according to eq. 6 may be calculated by multiplying E_c with a coefficient $\alpha_E = 1.2; 1.2; 0.9$ or 0.7 , respectively.

The modulus of elasticity at an age $t \neq 28$ days, $E_c(t)$, may be estimated from eq. 7:

$$E_c(t) = E_c \cdot \exp \left[\frac{s}{2} \cdot (1 - (28/(t/t_1))^{0.5}) \right] \quad (7)$$

where E_c = modulus of elasticity from eq. 6;

s = coefficient which depends on the type of cement;
 $s = 0.2; 0.25; 0.38$ for concretes made with rapid hardening high strength cement (RS), normal (ordinary) or rapid hardening cement (N,R) and slowly hardening cement (SL), respectively;

t = age of concrete in [days], taking into account curing temperature T according to eq. 17;

$t_1 = 1$ day.

The effect of elevated and reduced temperatures on the modulus of elasticity of concrete at an age of 28 days may be estimated from eq. 8:

$$E_c(T) = E_c \cdot (1.06 - 0.003 T/T_0) \quad (8)$$

where $E_c(T)$ = modulus of elasticity at the temperature T ;

E_c = modulus of elasticity at $T = 20^\circ\text{C}$ from eq. 6;

T = temperature of concrete in $^\circ\text{C}$;

$T_0 = 1^\circ\text{C}$.

Eq. 8 is primarily valid if no moisture exchange takes place. It may also be used for other concrete ages than 28 days.

Prediction of the Creep Coefficient

The creep coefficient at time t , $\phi(t, t_0)$, when concrete is loaded at time $t_0 < t$, may be estimated from the following general relation:

$$\phi(t, t_0) = \phi_{RH} \cdot \beta(f_{cm}) \cdot \beta(t_0) \cdot \beta_c(t - t_0) \quad (9)$$

$$\text{where } \phi_{RH} = 1 + \frac{1 - \frac{RH}{RH_0}}{0.46 \cdot (h/h_0)^{1/3}} \quad (10)$$

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$$\beta(f_{cm}) = \frac{5.3}{(f_{cm}/f_{cm0})^{0.5}} \quad (11)$$

$$\beta(t_0) = \frac{1}{0.1 + (t_0/t_1)^{0.2}} \quad (12)$$

$$\beta_c(t-t_0) = \left[\frac{(t-t_0)/t_1}{\beta_H + (t-t_0)/t_1} \right]^{0.3} \quad (13)$$

$$\text{with } \beta_H = 150 \cdot \left[1 + (1.2 \cdot \frac{RH}{RH_0})^{18} \right] \cdot \frac{h}{h_0} + 250 < 1500 \quad (14)$$

where RH = relative humidity of the ambient environment in [%];

h = $2A_c/u$; A_c = cross-section of the structural member in $[mm^2]$; u = perimeter of the structural member in contact with the atmosphere in $[mm]$;

f_{cm} = mean compressive strength of concrete in $[N/mm^2]$ at the age of 28 days;

t = age of concrete in [days] at the moment considered;

t_0 = age of concrete at loading in [days];

and $RH_0 = 100\%$, $h_0 = 100\text{ mm}$, $f_{cm0} = 10\text{ N/mm}^2$, $t_1 = 1\text{ day}$.

Effect of Type of Cement

The effect of type of cement on the creep coefficient of concrete may be taken into account by modifying the age at loading t_0 according to eq. 15:

$$t_0 = t_{0,T} \cdot \left[\frac{9}{2 + (t_{0,T}/t_{1,T})^{1.2}} + 1 \right]^\alpha > 0.5\text{ days} \quad (15)$$

where $t_{0,T}$ = age of concrete at loading in [days] according to eq. 17;

$t_{1,T} = 1\text{ day}$;

α = coefficient which depends on type of cement;

$\alpha = \begin{cases} -1 & \text{for slowly hardening cement, SL} \\ 0 & \text{for normal or rapid hardening cement, N or R,} \\ 1 & \text{for rapid hardening high strength cement, RS.} \end{cases}$

The value for t_0 according to eq. 15 has to be used in eq. 12; the duration of loading $t-t_0$ to be used in eq. 13 is the actual time under load in [days].

Effect of Elevated Temperatures

The creep coefficient at elevated temperatures may be roughly estimated from eq. 16:

$$\phi_T(t, t_0) = \phi_{T,st}(t, t_0) + \Delta\phi_{T,trans} \quad (16)$$

where $\phi_{T,st}$ = steady state creep coefficient, which may be calculated using eq. 9 ($\phi_{T,st}(t, t_0) = \phi(t, t_0)$) and eqs. 10 to 15, considering the modifications given in eqs. 17 to 20;

$\Delta\phi_{T,trans}$ = transient creep coefficient which may be estimated from eq. 21.

Effect of Elevated Temperatures - Steady State Creep

The effect of an elevated temperature T to which concrete is exposed prior to or during loading - the load being applied after temperature rise - may be taken into account employing eqs. 17 to 20:

$$t_T = \sum_{i=1}^n \Delta t_i \cdot \exp \left[13.65 - \frac{4000}{273 + T(\Delta t_i)/T_0} \right] \quad (17)$$

where t_T = modified age of concrete at loading in [days], which has to be used in eqs. 7 and 15;

$T(\Delta t_i)$ = temperature in [°C] during the time period Δt_i ;

Δt_i = number of days prior to loading, where the temperature T prevails;

T_0 = 1 °C.

$$\beta_{H,T} = \beta_H \cdot \exp \left[\frac{1500}{273 + T/T_0} - 5.12 \right] \quad (18)$$

where $\beta_{H,T}$ = temperature dependent coefficient replacing β_H in eq. 13;

β_H = coefficient according to eq. 14.

$$\phi_{RH,T} = \phi_T + [\phi_{RH} - 1] \cdot \phi_T^{1.2} \quad (19)$$

$$\text{with } \phi_T = \exp [0.015 \cdot (T/T_0 - 20)] \quad (20)$$

where $\phi_{RH,T}$ = temperature dependent coefficient which replaces ϕ_{RH} in eq. 9;

ϕ_{RH} = coefficient according to eq. 10.

In eqs. 18 and 20, T is a constant temperature while concrete is under load and $T_0 = 1$ °C.

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Effect of Elevated Temperatures - Transient Creep

Transient temperature conditions, i.e. the increase of temperature while the structural member is under load, leads to an additional creep $\Delta\phi_{T,trans}$, which may be calculated from eq. 21:

$$\Delta\phi_{T,trans} = 0.0004 \cdot (T/T_0 - 20)^2 \quad (21)$$

where T is the temperature in $[^{\circ}\text{C}]$ to which the structural member, being under load, is heated and $T_0 = 1^{\circ}\text{C}$.

Effect of High Constant Stresses

For stresses in the range of $0.4 f_c(t_0) < \sigma_c < 0.6 f_c(t_0)$, where $f_c(t_0)$ is the mean compressive strength of concrete at the age t_0 , the increased creep due to stress level dependent nonlinearity may be taken into account using eq. 22:

$$\phi_{\bar{\sigma}}(t, t_0) = \begin{cases} \phi(t, t_0) \cdot \exp[\alpha_{\sigma}(\bar{\sigma} - 0.4)] & \text{for } 0.4 < \bar{\sigma} < 0.6 \\ \phi(t, t_0) & \bar{\sigma} < 0.4 \end{cases} \quad (22)$$

where $\phi(t, t_0)$ = creep coefficient according to eq. 9;

$\bar{\sigma}$ = stress-strength ratio $\sigma_c/f_c(t_0)$;

α_{σ} = 1.5.

For mass concrete and for creep at very high relative humidities the coefficient α_{σ} may be as low as $\alpha_{\sigma} = 0.5$.

Comparison with Test Data and Applicability of the Model

Eq. 6 is a rather crude empirical relation between strength and stiffness of hardened concrete. As a consequence, a considerable scatter band is observed if test results on the modulus of elasticity are plotted versus the compressive strength of the concrete (Fig. 2). However, a clear tendency may be observed which is predicted reasonably well by eq. 6. The cubic root of the compressive strength correlates better with E_c than the square root, which underlies corresponding models in some other codes.

Fig. 3 illustrates the development of the modulus of elasticity with time as observed in more than hundred different tests taken from the literature (solid lines) and as evaluated from eq. 7 (dashed lines).

Apparently, the effect of aging upon the modulus of elasticity is reasonably well predicted by the CEB model. It is worth noting that the time function for the development of modulus of elasticity differs from that for the development of strength as given in [1].

The coefficient of variation for the prediction of the creep function, i.e. the sum of elastic and creep strains per unit stress, has been found to be $V = 20,4\%$. More refined models will result in lower coefficients of variation. However, the room for improvements is limited [2]. Fig. 4 illustrates the prediction accuracy for the effects of age at loading and type of cement on creep of concrete; $\epsilon_{cc,365}(t_0)$ represents the creep strain after a duration of loading of 365 days when the age at loading is t_0 . Here, the test results for concretes made of rapid hardening high strength (RS) and slowly hardening (SL) cements taken from various authors and represented by symbols have been converted to normal or rapid hardening (N,R) cements using eq. 15. Two examples of the prediction for the creep function are illustrated in Figs. 5 and 6. Further comparisons are shown in [2].

It has to be pointed out, that the simple formulae to predict the effects of elevated temperatures and high stresses upon creep allow only a very rough estimate of the mean concrete behavior. The restrictions of applicability given in [1] and in the basic document [2] have to be followed. Nevertheless, in many cases of practical significance, above all for creep of ordinary structural concrete at high ambient humidity (or thick structural members), satisfactory results may be obtained for the prediction of temperature effects. This is underlined by the example of Fig. 7, where relative creep strains as predicted by the model and experimental results of [11] are compared.

As far as the creep prediction at normal temperatures and stress levels is concerned the CEB MC 90 model resembles some of the features of the model given in the CEB-FIP Model Code 1970 [6] and of the model proposed by ACI Committee 209 [5]. However, various basic improvements could be achieved. The time development of creep which is described by a hyperbolic function (eq. 13) includes the member size as a parameter taking pattern from diffusion theory. In addition, the effects of the ambient environment and member size on creep of concrete are interrelated (eq. 10). Nevertheless, the chosen product model inevitably includes the typical constitutive weaknesses of these models as indicated in Fig. 1. Further informations and restrictions of validity of the model have been discussed in [2].

SHRINKAGE

The prediction model for shrinkage given in the CEB-FIP Model Code 1990 predicts the mean time dependent strain of a non-loaded, plain structural concrete member which is exposed to a dry or moist environment after curing. The model is valid for ordinary normal weight structural concrete, moist cured at normal temperatures not longer than 14 days and exposed to mean relative humidities in the range of 40 to 100 percent at mean temperatures

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ranging from 5 °C to 30 °C. Some extensions of the model have been developed to allow an estimate of the effect of temperature upon shrinkage [1]. Details, in particular on the applicability of the relations presented, may be found in [2].

Prediction Formulae

The strain due to shrinkage or swelling at normal temperatures may be calculated from eq. 23:

$$\epsilon_{cs}(t, t_s) = \epsilon_{cso} \cdot \beta_s(t - t_s) \quad (23)$$

where ϵ_{cso} = notional shrinkage coefficient according to eq. 24;

β_s = coefficient to describe the development of shrinkage with time according to eq. 28;

t = age of concrete in [days];

t_s = age of concrete in [days] at the beginning of shrinkage or swelling.

The notional shrinkage coefficient may be obtained from eq. 24:

$$\epsilon_{cso} = \epsilon_s(f_{cm}) \cdot \beta_{RH} \quad (24)$$

with

$$\epsilon_s(f_{cm}) = [160 + 10 \cdot \beta_{sc} \cdot (9 - f_{cm}/f_{cmo})] \cdot 10^{-6} \quad (25)$$

where β_{sc} = coefficient which depends on type of cement;

$$\beta_{sc} = \begin{cases} 4 & \text{for slowly hardening cement, SL} \\ 5 & \text{for normal or rapid hardening cement, N,R} \\ 8 & \text{for rapid hardening high strength cement, RS,} \end{cases}$$

and

$$\beta_{RH} = \begin{cases} -1.55 \cdot \beta_{sRH} & \text{for } 40\% < RH < 99\% \\ +0.25 & \text{for } RH > 99\% \end{cases} \quad (26)$$

$$\text{where } \beta_{sRH} = 1 - \left(\frac{RH}{RH_0}\right)^3 \quad (27)$$

In eqs. 25 and 27, f_{cm} is the mean compressive strength of concrete in [N/mm²], and RH is the mean relative humidity of the ambient atmosphere in [%], respectively; $f_{cmo} = 10$ N/mm² and $RH_0 = 100\%$.

The development of shrinkage with time is given by:

$$\beta_s(t - t_s) = \left[\frac{(t - t_s)/t_1}{\beta_{sH} + (t - t_s)/t_1} \right]^{0.5} \quad (28)$$

$$\text{with } \beta_{sH} = 350 \cdot (h/h_0)^2 \quad (29)$$

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where $t-t_s$ = duration of drying or swelling in [days], $h = 2A_c/u$ (A_c = cross-section of the structural member in $[\text{mm}^2]$; u = perimeter of the structural member in contact with the atmosphere in $[\text{mm}]$), $h_0 = 100 \text{ mm}$ and $t_1 = 1 \text{ day}$.

Effect of Elevated Temperatures

The effect of elevated temperatures T on shrinkage of concrete may be taken into account using eqs. 30 to 32:

$$\beta_{\text{SHT}} = \beta_{\text{SH}} \cdot \exp [-0.06 (T/T_0 - 20)] \quad (30)$$

where β_{SHT} = temperature dependent coefficient replacing β_{SH} in eq. 28;

β_{SH} = coefficient according to eq. 29.

$$\beta_{\text{RH},T} = \beta_{\text{RH}} \cdot \beta_{\text{ST}} \quad (31)$$

$$\text{with } \beta_{\text{ST}} = 1 + \left[\frac{8}{103 - 100 \text{ RH}/\text{RH}_0} \right] \cdot \left[\frac{T/T_0 - 20}{40} \right] \quad (32)$$

where $\beta_{\text{RH},T}$ = temperature dependent coefficient which replaces β_{RH} in eq. 24;

β_{RH} = coefficient according to eq. 26.

In eqs. 30 and 32, T is a constant temperature, $T_0 = 1^\circ\text{C}$ and $\text{RH}_0 = 100\%$.

Comparison with Test Data and Applicability of the Model

When optimizing shrinkage prediction a total of 27 sets of experiments, i.e. 103 individual shrinkage tests have been used. In Fig. 8 measured shrinkage and the predicted values are compared for one set of experimental data [14]. It is obvious that both the time development of shrinkage and the effect of member size are predicted reasonably well by the model given above.

Similar to creep, also for the prediction of shrinkage, the compressive strength of concrete is taken into account. Actually, the parameter strength has per se no effect upon shrinkage. Shrinkage actually depends on the moisture loss of concrete due to drying. However, since higher strength concretes are made with lower water-cement ratios the amount of water which is lost due to drying generally decreases as concrete strength increases. This is, no doubt, a crude approach. However, it should be kept in mind that the designer who uses the CEB MC 90 does not know the water content of a concrete to be used in a particular structure. In addition, shrinkage is affected by the type of cement even if the compressive strength of concretes under consideration

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at the age of 28 days is the same. Both, the effects of strength of concrete and type of cement upon shrinkage are taken into account by eq. 25 which is verified in Fig. 9. The scatter of test data is very large. Obviously, the relation expressed in eq. 25 is a rather crude description of the real effects upon shrinkage, and as a consequence much of the prediction error which is observed for the shrinkage model is caused by this approach. However, the relations are statistically significant, and the overall accuracy is improved if the parameters compressive strength and type of cement are taken into consideration in the shrinkage prediction.

Though the coefficient of variation $V = 33\%$ for the CEB MC 90 approach is still high, a considerable improvement of the shrinkage prediction could be achieved compared with the previous CEB models. This is true both for the prediction accuracy and the principles of the approach. For further details refer to [2].

SUMMARY AND CONCLUSIONS

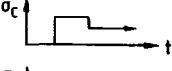
1. For the prediction of creep of concrete a suitable product type model has been chosen for presentation in the new CEB-FIP Model Code. It has been optimized on the basis of a comprehensive computerized data bank. The coefficient of variation for the prediction of the creep function has been found to be approximately 20 %.
2. Preference has been given to the product type over the summation type creep approach for the sake of simplicity and conciseness of code-type product models. However, besides informations on the new prediction models, a suitable linear summation model is presented in a CEB manual.
3. Though the new CEB creep model resembles some of the features of the models given in CEB MC 70 or the model presented by ACI 209, various basic improvements could be achieved.
4. For the prediction of shrinkage, a well established diffusion theory type model has been chosen and optimized using the data bank. The coefficient of variation has been found to be approximately 33 %.
5. The developed prediction models, both for creep and shrinkage represent a reasonable compromise of accuracy and simplicity. It is felt that they meet the requirements to be operational and suitable for presentation in a code.

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load history	criterion	accuracy of prediction	
		product model	summation model
constant stress	effect of age at loading	+	o
	time development	+	o
increasing stress		o	o
decreasing stress		o	o
		-	o
relaxation	very young age at loading and thick member or high relative humidity	-	o
	other cases	o	o

legend: (+) good; (o) acceptable; (-) poor

Fig. 1—Comparison of the accuracy of the product model and the summation model for the prediction of creep

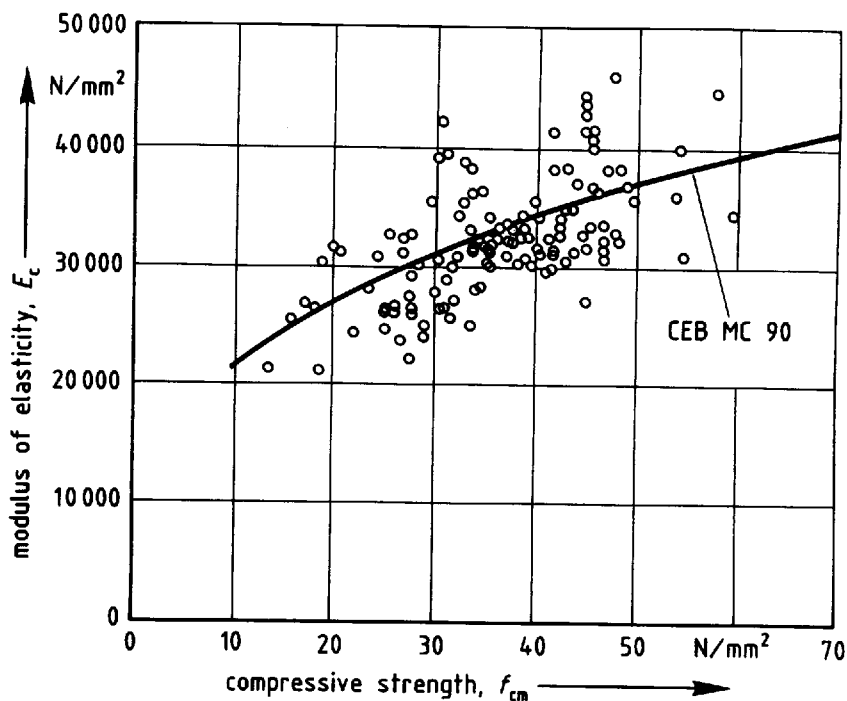


Fig. 2—Relation between the compressive strength of concrete and the modulus of elasticity

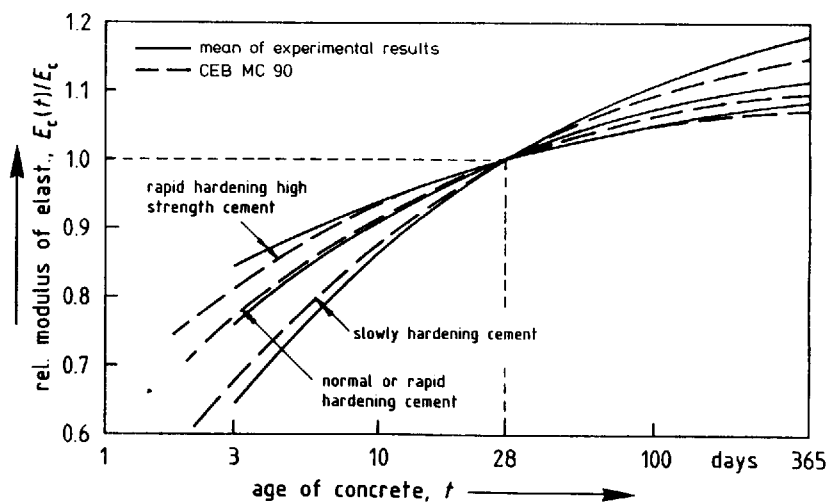


Fig. 3—Development of the modulus of elasticity with time

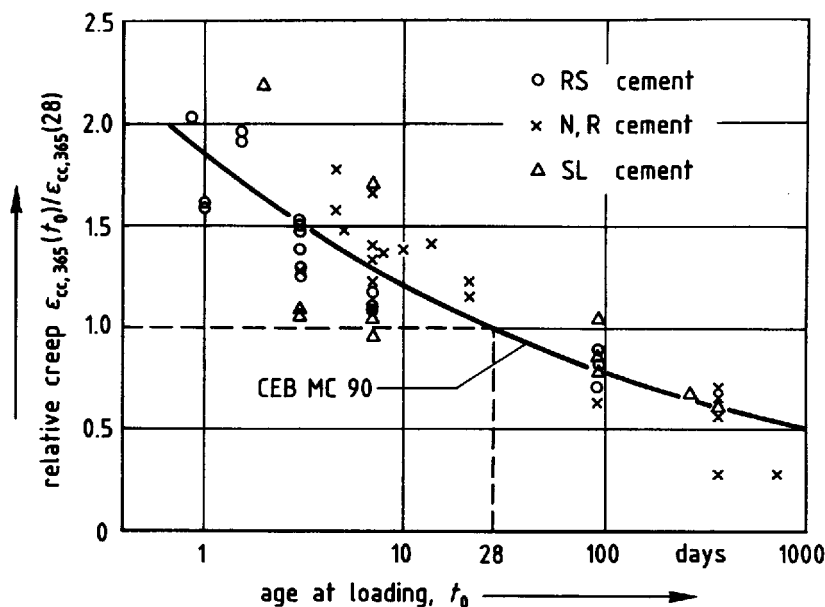


Fig. 4—Effects of age at loading and type of cement on the magnitude of creep of concrete

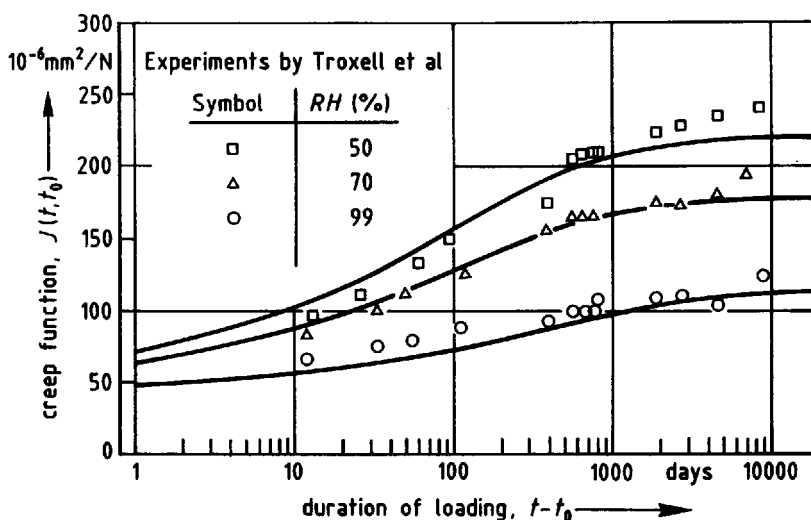


Fig. 5—Comparison of measured [12] and predicted (CEB MC 90, solid line) creep functions. Test data: $f_{cm} = 16.9 \text{ N/mm}^2$; c-type: N,R; $2A_c/u = 51 \text{ mm}$; RH = 99/70/50%; $t_0 = 28 \text{ days}$

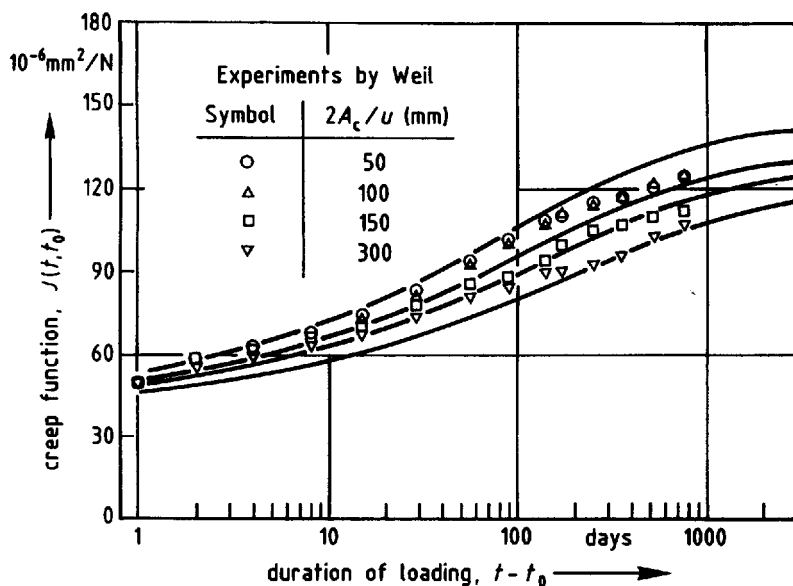


Fig. 6—Comparison of measured [13] and predicted (CEB MC 90, solid line) creep functions. Test data: $f_{cm} = 25.4 \text{ N/mm}^2$; c-type: SL; $2A_c/u = 50/100/150/300 \text{ mm}$; $RH = 65\%$; $t_0 = 28 \text{ days}$

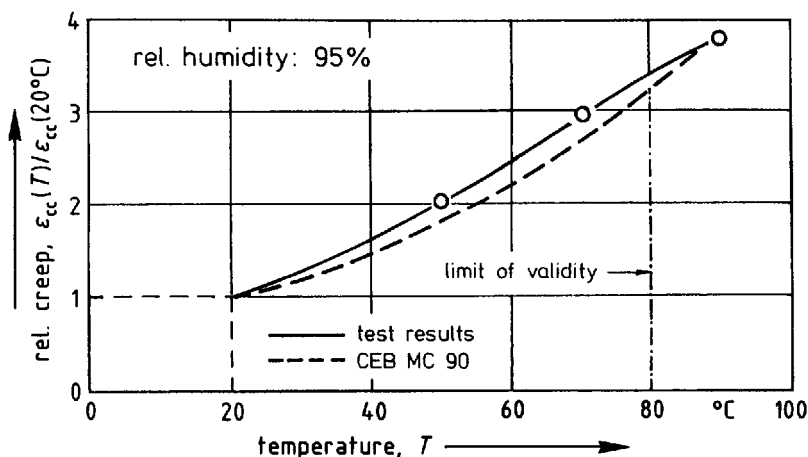


Fig. 7—Effect of elevated temperature upon creep of concrete — Test results [11] and prediction (dashed line)

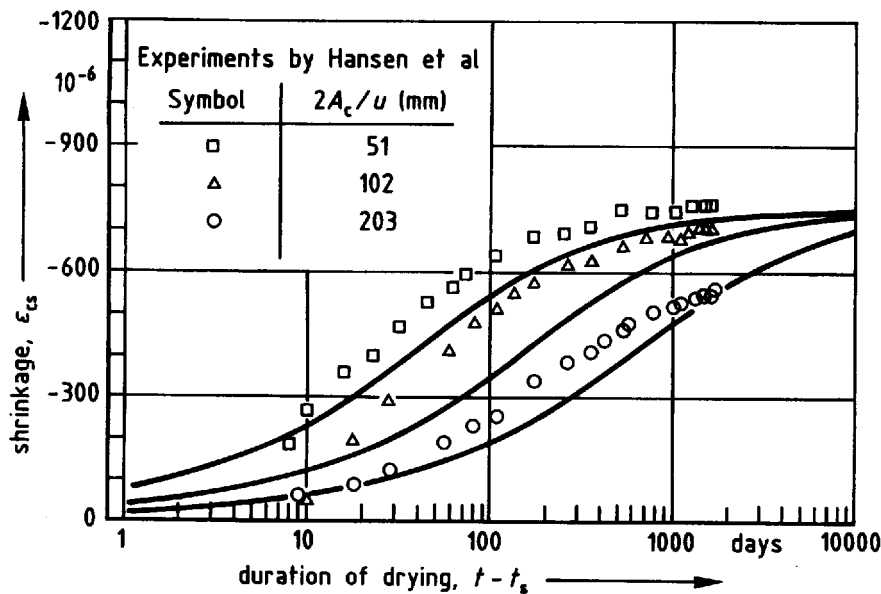


Fig. 8—Comparison of measured [14] and predicted (CEB MC 90, solid line) shrinkage; Test data: $f_{cm} = 41.3 \text{ N/mm}^2$; c-type: RS; $2A_c/u = 203/102/51 \text{ mm}$; $RH = 50\%$; $t_s = 8 \text{ days}$

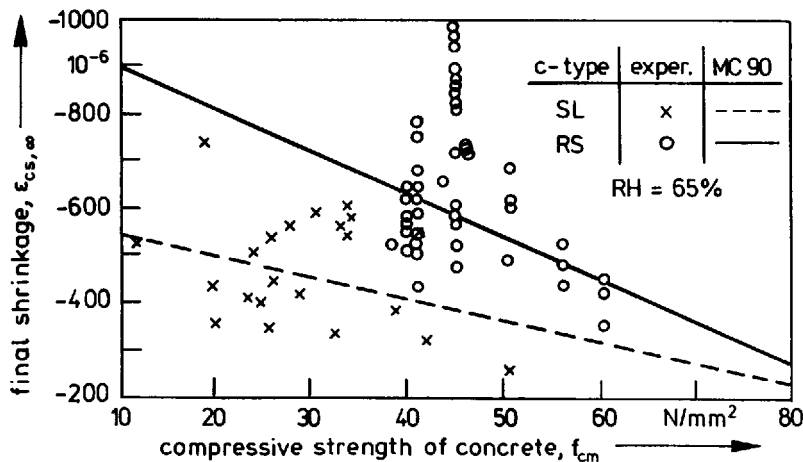


Fig. 9—Relation between the final shrinkage and the compressive strength of concretes made with slowly hardening (SL) and rapid hardening high strength (RS) cements — Predictions of CEB MC 90 and experimental results which have been converted for $RH = 65\%$ by means of eq. 27 where necessary

SP 135-2

Creep and Shrinkage of Concrete as Affected by Admixtures and Cement Replacement Materials

by J.J. Brooks and A. Neville

Synopsis:

The paper reviews the influence on creep and shrinkage of water reducers, retarders and accelerators, and superplasticizers. Few generalizations can be made.

Partial replacement of cement by fly ash or blastfurnace slag leads to reduced creep except for early age loading. Specific properties of the materials used affect creep. Data on the use of microsilica suggest that it increases creep.

Because of the paucity of data available, reliable deductions about the influence of various materials cannot be made and, in important cases, experimental determination of creep and shrinkage of concrete with the actual mix ingredients may be necessary.

Keywords: Accelerating agents; admixtures; blast furnace slag; cements; creep properties; fly ash; plasticizers; shrinkage; silica fume; superplasticizers

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INTRODUCTION

In recent years, there has been a considerable increase in the use of concrete containing fly ash (pfa) and ground granulated blastfurnace slag and also in the use of a wide range of admixtures. It is therefore useful to update our review of six years ago (1). Moreover, on that occasion, shrinkage was not considered in detail so that an inclusion of this topic in the present paper has necessitated an examination of some older publications.

The approach used is largely empirical as attempts to establish fundamental relationships are believed to be unjustified at this stage in view of our continuing lack of a full understanding of the mechanism of creep.

For the present paper, we shall consider as admixtures all those materials which are used in small dosages, and refer to those used in larger quantities as cement replacement materials. The effect of all these materials on long-term deformation is probably the least researched aspect of properties of concrete. It is usually tacitly assumed that, if there are no detrimental effects on strength, long-term deformations will not be changed drastically. Nevertheless, possible changes need to be assessed for economical design and serviceability requirements of concrete structures.

In most investigations on the effect of materials added to concrete, creep, shrinkage and swelling are quantified in terms of relative values, i.e. the deformation of the concrete containing the admixture or cement replacement material as a percentage of the plain (control) concrete. This is not necessarily a sound approach as the two concretes have different properties in other respects as well.

Moreover, basic creep (sealed or moist-stored concrete) is often affected in a different way from creep under drying conditions. Nevertheless, reporting relative values has the merit of simplicity.

WATER-REDUCERS

The influence of water-reducers (plasticizers) on creep and shrinkage is summarized in Table 1. The majority of results are for concrete having a similar workability and strength as their respective control concretes, so that the use of the admixture permitted a reduction in both the water and the cement contents. The concrete, therefore, contained less cement paste, which is the material that undergoes creep. For these cases, relative creep is based on equality of stress (specific creep), although relative values based on the equality of stress/strength ratio are similar. The same situation applies also when the admixture is used solely to enhance workability. However, when the admixture is used to reduce the water/cement ratio and, hence, increase strength, relative creep needs to be expressed both on a specific creep and a constant stress/strength ratio basis. The latter allows approximately for a change in the water/cement ratio so that the relative creep reflects the effect of admixture per se.

On the other hand, the influence of an admixture on shrinkage can be assessed confidently only when it is used solely to increase the workability. Unfortunately, only very few data are available (6, 9) and these suggest a small increase in shrinkage. In other cases, changes in cement content and in water content affected shrinkage so that the relative shrinkage values reflect the combined action of those changes as well as of the admixture.

Table 1 shows that the variations in the relative deformation are considerable: 34-166 per cent for creep; 25-212 per cent for shrinkage; and 76-210 per cent for swelling. Consequently, only very general observations can be made. It appears that lignosulphonate admixtures lead to a higher basic creep than carboxylic acid admixtures, the latter often even resulting in a reduction in basic creep compared with plain concrete. Under drying conditions, the effects of the different admixtures on creep and shrinkage are not consistent.

For conditions approximating to basic creep, the relative creep of concrete containing a water-reducing admixture increases as the age at loading increases, (3, 5) but the same influence is not apparent for drying concrete.

The wide range of relative deformation cannot be explained by factors which affect the absolute values of creep and shrinkage. For example, there is no consistent trend when there is a change in the cement paste content (2, 3, 7, 9), in the type of aggregate (2, 3, 7) or in the composition of cement. (4)

RETARDERS AND ACCELERATORS

There do not appear to be any publications dealing with creep and shrinkage of set-retarding admixtures (ASTM C494-82, type B). For accelerating admixtures (types C and E), there have been no further publications since our last review, (1) which indicated an increased basic creep (122-136 per cent) for calcium chloride; corresponding values for drying creep were 131-203 per cent, and 133 per cent for shrinkage. A combination of lignosulphonate and triethanolamine increased basic creep (110-125 per cent), but under drying conditions, creep had a relative value of 92-135 per cent, and shrinkage was 110 per cent. The foregoing effect on creep was greater for an earlier age at loading (5). Other work (6) showed an increase in shrinkage (105-117 per cent) for admixture combinations of lignosulphonate and calcium chloride, and lignosulphonate and triethanolamine. The relative values of creep were as follows:

<u>Admixture</u>	<u>Moist-stored</u>	<u>Dry-stored</u>
Lignosulphonate) plus) calcium chloride)	80 per cent	154 per cent
Lignosulphonate) plus) triethanolamine)	93 per cent	179 per cent

SUPERPLASTICIZERS

Table 2 has been compiled in the same manner as Table 1 and summarizes detailed experimental data on the effects of superplasticizing admixtures (high-range water reducers) (ASTM C 494-82, types F and G) on creep and shrinkage. It seems that the overall situation is similar to that in the case of plasticizers in that there is a wide variation of relative deformation and a lack of consistency of influencing factors. For instance, when admixtures are used to make flowing concrete, relative basic creep ranges from 81-117 per cent (9, 11, 12). On the other hand, there seems to be evidence that shrinkage increases by approximately 10 per cent (9, 13, 16).

Other publications, which are not included in Table 2 because precise experimental details are lacking, indicate little or not effect of superplasticizers on shrinkage (17-23), reduced shrinkage (24, 25), and increased shrinkage (26).

With respect to creep under drying conditions, any superplasticizer effect probably depends on the time when shrinkage occurs. According to Table 2, pre-drying before loading reduces relative creep (16), but when drying commences at the same time as loading relative creep is either unchanged (10) or increased up to 156 per cent (9-11).

There are few data on deformation of concrete having a similar workability and increased strength through the use of a superplasticizer, the available evidence (10, 14, 15) suggesting a similar or reduced shrinkage because of the lower water content of the superplasticized concrete. However, creep at a constant stress/strength ratio is generally increased, and more consistently so for basic creep.

On the basis of Table 2, it is not possible to deduce any influence of type of superplasticizer on deformation. Current research at the University of Leeds has demonstrated small increases in shrinkage for SNF (sulphonated naphthalene formaldehyde condensate) and SMF (sulphonated melamine formaldehyde condensate) of 106 and 112 per cent, respectively, but greater increases for copolymer and MLS (modified lignosulphonate) of 124 and 137 per cent, respectively. It seems that appreciable increases in shrinkage are associated with the ability of the superplasticizer to entrain air because a four-per cent air entrained concrete (AEA) exhibited similar trends (Fig.1).

Corresponding creep tests under drying conditions indicated a relative creep of approximately 120 percent for copolymer and MLS admixtures, and little change for SNF and SNF superplasticizers.

The foregoing observations confirm that entrained air can be regarded as aggregate with a zero modulus of elasticity so that resistance of the concrete to deformation is less (1). There appears to have been no further research on the subject of deformation of air entrained concrete since our last review (1).

CEMENT REPLACEMENT MATERIALS

Partial replacement of cement by fly ash or blastfurnace slag is often accompanied by a reduction in the water/cementitious material ratio compared with a plain cement mix so as to achieve a similar workability. As before, the influence on creep of the water/cementitious material ratio can be allowed for in an approximate manner by comparing the creep values on the basis of equal stress/strength ratio. Since, in many cases, the chief advantage of the use of replacement materials is the reduction in the heat of hydration in large volume pours, most of the relevant tests have been obtained using sealed or moist-stored concrete specimens.

The influence of partial replacement of cement to fly ash on basic creep is shown in Fig.2. Apart from early-age loading, creep is reduced as the replacement level increases up to approximately 35 per cent, although the range of creep values suggests that other factors such as age or maturity and type of fly ash may also play a role. It is of interest to note that relative specific creep follows the same trend as Fig.2 for mature concrete but, for loading at early ages, the relative value of specific creep is much greater because of the low strength and, therefore, low stress applied to the fly ash concrete.

Partial replacement of cement by blastfurnace slag has a similar influence on basic creep as Fig.3 demonstrates, but data exist to show that the decrease in creep extends to a higher replacement level of 75 per cent.

Basic creep at very early ages is of interest in connexion with its role of relieving stresses induced by restraint to differential thermal movement arising from the heat of hydration. Ideally, a concrete having a low creep is desirable in order to avoid relief of induced compression when the temperature is increasing. However, experimental simulation of stress and temperature at very early ages is difficult, and the assessment of replacement materials for this application remains outstanding.

For general structural concrete with replacement materials, very few creep and shrinkage results are available. Figure 4 suggests that creep under drying conditions is reduced when fly ash is used while Fig.5 indicates the opposite effect for cement replacement by slag. Such apparent contrasting behaviour must be regarded as tentative. It is likely that the type of material is also a factor in creep. For example, the highest values in Fig.5 are for high magnesia slag (40) and creep appears to be lower the higher the gypsum content (42).

The available evidence suggests shrinkage of fly ash and blast furnace slag concretes is similar in pattern (Figs. 6 and 7). When the water/cementitious material ratio remains unchanged partial replacement increases shrinkage, but when the water/cementitious material ratio is reduced so as to maintain the same workability as the control concrete shrinkage is either unchanged or slightly reduced.

SILICA FUME

Silica fume (microsilica) is used either in small quantities to improve concrete properties or in larger quantities to achieve very high strength and durability. The effect on creep and shrinkage has yet to be determined in detail but some Japanese data (43) are of interest. These are for concretes having various cement contents and water/cementitious material ratios with 30 per cent of the cement replaced by microsilica; a superplasticizer was used to

achieve the required workability. For the same water/cementitious material ratio, the strength of microsilica concrete was 30 per cent greater than that of the control concrete, and creep and shrinkage were adjusted on the basis of equal cement paste volume as well as strength. Compared with the control concrete, the microsilica concretes exhibited:

- similar shrinkage after moist curing;
- approximately 50 per cent more creep under drying conditions after moist curing;
- approximately 15 per cent more creep under drying conditions after moist curing;
- less basic creep after autoclaved curing;
- more basic creep after moist curing.

CONCLUSIONS

The present review discloses a general paucity of data on creep and shrinkage of concretes with admixtures and replacement materials. In particular, the available data, which cover a wide range of test conditions (eg. see Tables 1 and 2), do not make it possible to produce reliable generalizations about the effects of the various materials. It appears thus that the use of these materials, especially of cement replacement materials, has outstripped the knowledge of their effects on what often are important properties of concrete.

It follows that, when creep or shrinkage are critical, test data on mixes with the actual ingredients may be necessary. Accelerated test methods in conjunction with analytical extrapolation methods may be useful (44-47).

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