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Concrete creep and shrinkage at cyclic ambient conditions

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Abstract

The paper presents an experimental study on creep and shrinkage of concrete both at variable and constant ambient conditions. The considered variable ambient conditions correspond to the natural climatic variations present in Belgium. The following parameters were examined: period (season) when the concrete was cast and loaded, cement type and concrete composition. Both sealed and unsealed cylindrical specimens were used. The experimental results show that both the 'season' in which the concrete was cast and the 'humidity cycles' influence the shrinkage deformation. The creep coefficient, however, is mostly dependent on the 'season'. Two concrete creep and shrinkage models, available in literature, i.e. the model in Eurocode 2 (EC2) and the B3-model of ACI, have been used to predict the results of the reference specimens (constant ambient conditions).

Research significance: The main objective of the present research was to study the effect of variable ambient temperature and relative humidity on creep and shrinkage of concrete. The results of the study will provide information on the effect of these factors on the time-dependent deformations of concrete and also help in modifying the present concrete creep and shrinkage models. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Creep; Shrinkage; Variable ambient conditions

1. Introduction

Probably the most uncertain and most difficult aspect of the design of reinforced and prestressed concrete structures is the prediction of time-dependent behaviour. However, realistic prediction of concrete creep and shrinkage is of crucial importance for durability and long-time serviceability of concrete structures, and in some cases also for long-time stability and safety against collapse. Creep and shrinkage cause increases in deflection and curvature, cracking, losses of prestress and redistribution of stresses [8].

It is now clear that for creep and shrinkage sensitive structures, such as long span prestressed bridges, cooling towers and very tall buildings, it is very important to use a realistic creep and shrinkage model for the analysis of its time-dependent behaviour.

Creep and shrinkage are known to be influenced by many variable factors: cement type, W/C-ratio, curing conditions, relative humidity of the environment, age and size of member. In the literature, a considerable amount of experimental data are available concerning the effect of each of those variables. However, most of this information has been obtained from creep and shrinkage tests, carried out at constant temperature and relative humidity. As a result, in practical creep and shrinkage prediction models, hardly any reference is made to the influence of climatic variations in spite of the fact that, in practice, structures are very often exposed to variable ambient conditions (different seasons). From the little available information concerning the influence of variable ambient temperature and relative humidity on creep and shrinkage of concrete, no conclusive evidence on the related effects may be gained [1,10].

In order to acquire some knowledge regarding the problem of 'the prediction of creep and shrinkage due to a time-varying temperature and relative humidity' a joint research program has been executed in the Belgian Universities: Katholieke Universiteit Leuven (KUL), Universiteit Gent (UG) and Université Catholique de Louvain (UCL). The considered variable ambient conditions correspond to the natural cyclic variations present in Belgium.

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This paper presents a summary of the results of the KUL who was the initiator of the project. Complete details of the experimental work can be found in [2]. Besides, two creep and shrinkage prediction models, i.e. Eurocode 2 [4] and B3-model of ACI [5], have been used to predict the time-dependent behaviour of the loaded and unloaded specimens stored at constant temperature and relative humidity.

2. Experiments

For the experimental study of the time-dependent deformations of loaded and unloaded concrete, cylindrical specimens, exposed either to variable or to constant ($T = 20°\mathrm{C}$, $\mathrm{RH} = 60\%$) conditions, were used.

From the data of 15 official weather stations which were geographically spread all over Belgium, it followed that both temperature and relative humidity could be described by means of a sine curve [3] shown in Fig. 1.

Concrete creep and shrinkage are affected by many parameters. The factors investigated in this research were the following:

- type of cement:
  - CEM I 42,5 (KUL),
  - CEM III A 42,5 (UCL),
  - CEM I 52,5 (UG);
- cement content and W/C-ratio: three different concrete compositions (A1, A2 and A3) of which the mix proportions are given in Table 1.
- moment (season) when concrete is cast: the starting values of temperature and relative humidity of the 'four different seasons' were (Fig. 1):
  - spring (T1): $T = 12.5°\mathrm{C}$, $\mathrm{RH} = 77.5\%$,
  - summer (T2): $T = 20°\mathrm{C}$, $\mathrm{RH} = 65.0\%$,
  - autumn (T3): $T = 12.5°\mathrm{C}$, $\mathrm{R.H.} = 77.5\%$,
  - winter (T4): $T = 5°\mathrm{C}$, $\mathrm{RH} = 90.0\%$;
- moisture conditions of the specimens (Figs. 2 and 3):
  - sealed specimens (no water exchange with the environment: autogenous shrinkage – basic creep),
  - unsealed specimens (water exchange with the environment: drying shrinkage – total creep).

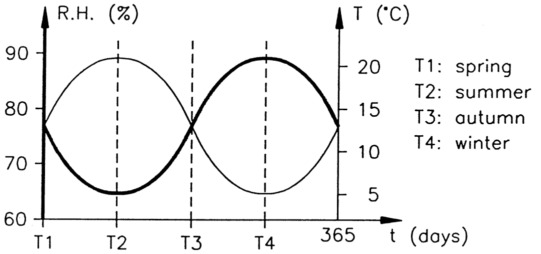

Fig. 1. Temperature and relative humidity in Belgium.

Table 1
Concrete mix proportions – mechanical properties

Parameter	Concrete type		
	A1	A2	A3
Mix design (kg/m^3)			
gravel 4/14	1280	1240	1200
sand 0/5	640	620	600
CEM I 42.5	280	350	425
Water	168	175	170
W/C	0.6	0.5	0.4
$f_{c,28,95}$ (N/mm^2)	30.2	40.4	51.0
Applied uniaxial constant stress ($= 1/3 f_{c,28,95}$) (N/mm^2)	10	12.5	15

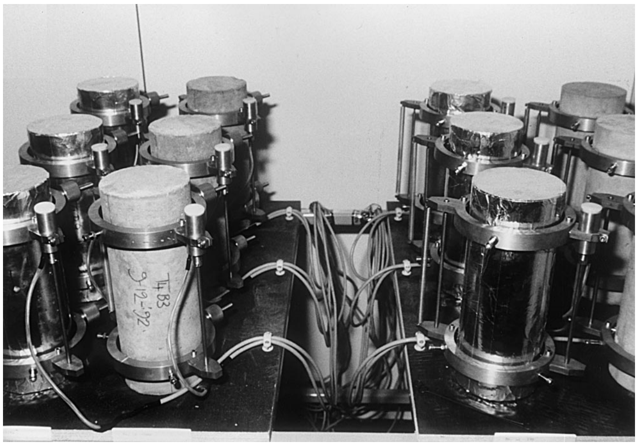

Fig. 2. Shrinkage test.

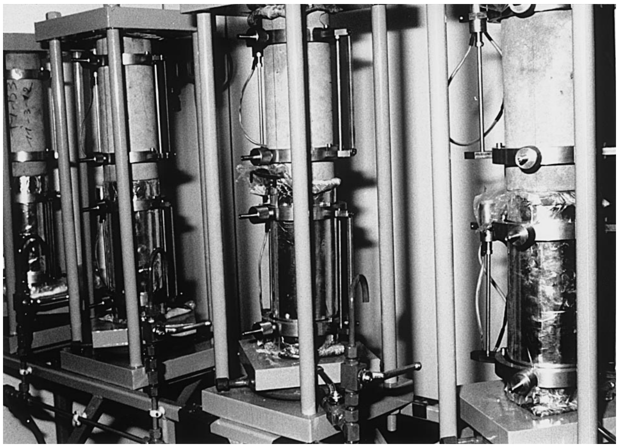

Fig. 3. Creep test.

The cylindrical specimens for the creep and shrinkage tests have a diameter (ϕ) of 120 mm and a height (h) equal to 300 mm.

The creep specimens were subjected to uniaxial loading. The compressive creep inducing stress σ_c was chosen equal to 1/3 of $f_{c,28,95}$ which is the compressive strength determined on cylinders ($\phi = 120$ mm, $h = 300$ mm), stored for 28 days in a wet room ($T = 20°\mathrm{C}$, $\mathrm{RH} \geqslant 95\%$). The value of $f_{c,28,95}$ for the three different concrete types can be found in Table 1.

The creep specimens were loaded as soon as the compressive strength of the companion cylinders, i.e., cylinders stored under the same climatic conditions as the creep specimens, reached $f_{c,28,95}$. Consequently, the age at loading varied for each season.

The creep and shrinkage tests at constant temperature (20°C) and relative humidity (60%), i.e. the reference tests, were carried out in a climatic room. The experiments at variable ambient conditions were conducted in the climate test chamber (4 m × 4 m) in which the desired cyclic variation of temperature and relative humidity can be simulated.

After manufacture, the cylinders (creep, shrinkage, compressive strength) were cured immediately under the respective climatic conditions. One day after casting they were demoulded and equipped with their measurement device (Fig. 2). The first recording of shrinkage was executed about 24 h after casting the specimen ($\Rightarrow t_0 = 1$).

The time-dependent deformations of the cylinders were measured by means of linear variable differential transducer (LVDT). They were installed in a frame made in brass (Fig. 4). The ring R1 is fixed on the cylinder by means of three screws (S1, S2 and S3). On the other hand, the ring R2 is only fixed by means of two screws (S4 and S5) which are located on the axis α–α so that ring R2 can rotate around α–α. The frame contains also two small bars in brass. The bar T1 with a length of 200 mm is kept in its place by means of a spring which is fixed onto the two rings R1 and R2. The bar at the opposite side (Fig. 5) where the relative displacement D (Fig. 4) of ring R1 with respect to R2 due to the deformation of the specimen (creep, shrinkage, extension due to a variation in temperature, ...) is measured, holds at one end the core of the LVDT. More details of the measurement device and the loading equipment of the creep tests are described elsewhere [2,7]. The 'deformations' as well as temperature and relative humidity in the climate chamber were recorded automatically.

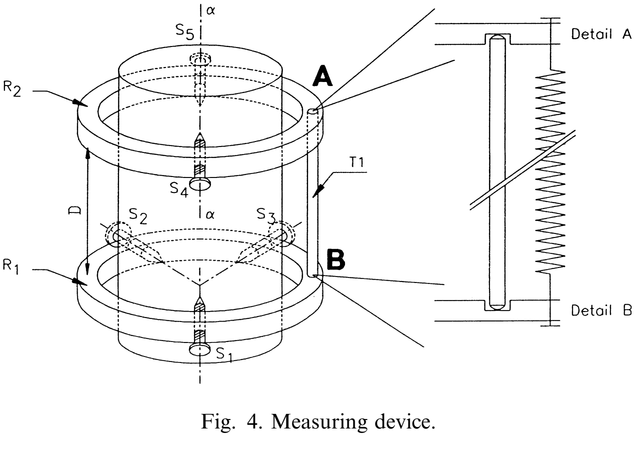

Fig. 4. Measuring device.

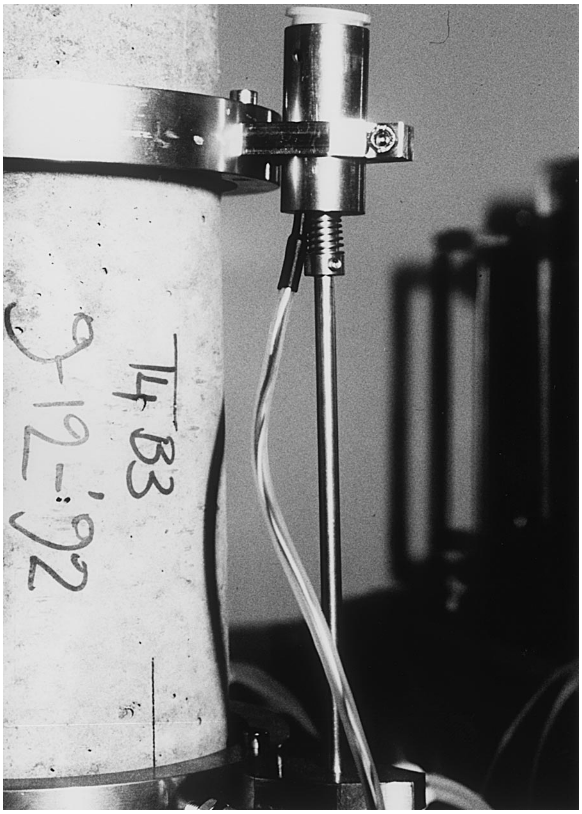

Fig. 5. Measuring device detail.

To obtain the correct strain of the specimen due to creep and/or shrinkage, the measured value had to be adjusted because of the following reasons:

- length change of the frame and concrete specimen due to a variable temperature,
- calibration of each LVDT.

The creep strain at a certain age of the concrete was obtained from the adjusted 'measured total strain' by subtracting the instantaneous elastic strain at loading and the strain at the same age of the corresponding unloaded specimen.

3. Results and discussion

From the test results it follows that in the present study the influence of the concrete mix composition (W/C-ratio, cement content) on the measured time-dependent deformations cannot be unequivocally proved. However, since the main objective was to investigate the influence of a variable ambient temperature and relative humidity on the creep and shrinkage of concrete, it seems obvious to consider for each ‘season’ the average of the results of the three different mixes (A1, A2 and A3).

3.1. Shrinkage

Fig. 6 shows the autogenous shrinkage test results of the sealed specimens stored at variable and constant climatic conditions, respectively. According to [6] the magnitude of autogenous shrinkage is of the order of 100×10^{-6} for ordinary concrete. However, although the cylinders were sealed with a self-adhesive aluminium sheet immediately after stripping, the obtained test results are much larger: at the age of 2300 days they amounted to about 300×10^{-6}.

Moreover, for the ‘season-specimens’ (T1, T2, T3 and T4) a sine wave trend is slightly noticeable in the test results. Probably the aluminium sheet was not 100% waterproof. As expected, the difference in autogenous shrinkage of specimens either stored under variable climatic conditions or at constant relative humidity is rather small.

Fig. 7 shows the test results of the unsealed specimens (drying shrinkage) stored at variable ambient and constant humidity, respectively. The sine wave trend of the relative humidity can be recognized in the shrinkage curves of the ‘season-specimens’ as expected. The length changes of the specimens due to variation of relative humidity are very pronounced. Besides, it can be observed that the shrinkage behaviour during the first months after casting the concrete is quite different for the four different ‘season’-concretes. However, afterwards, their shrinkage course shows a same tendency, i.e., a sine curve with a period of one year and an amplitude of about 55×10^{-6}.

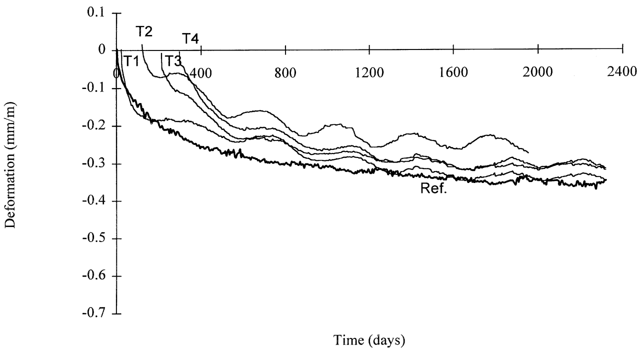

Fig. 6. Autogenous shrinkage – average of mixes A1, A2 and A3.

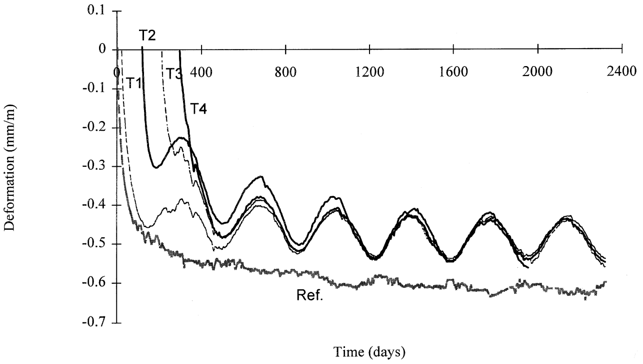

Fig. 7. Drying shrinkage – average of mixes A1, A2 and A3.

Furthermore Fig. 7 shows that the drying shrinkage of the reference specimens is constantly larger than the shrinkage of the ‘season’-specimens. This higher shrinkage is related to the fact that the constant relative humidity, which is equal to 60%, is continually smaller than the ambient humidity during the variable conditions (65–90%).

3.2. Creep

The creep coefficient, $\phi(t,t')$, is defined as the ratio of the creep strain at time t to instantaneous elastic strain in a specimen, subjected to constant stress, i.e.,

$$\phi(t,t') = \frac{\varepsilon_c(t,t')}{\varepsilon_c(t')},$$

where t' is the creep loading age.

Since the specimens were loaded at the time that the compressive strength of the companion cylinders reached $f_{c,28,95}$ the age of loading for the ‘season’-specimens was quite different.

The test results of the sealed specimens (basic creep) are shown in Fig. 8 and of the unsealed specimens (total creep) in Fig. 9, respectively. Contrary to the shrinkage diagrams all creep curves start in the origin of the time-axis, i.e. ‘$t - t' = 0$’ which corresponds to the moment of loading.

Both figures show that the increase of the creep coefficient within the first year after loading is influenced by the season in which the concrete was cast:

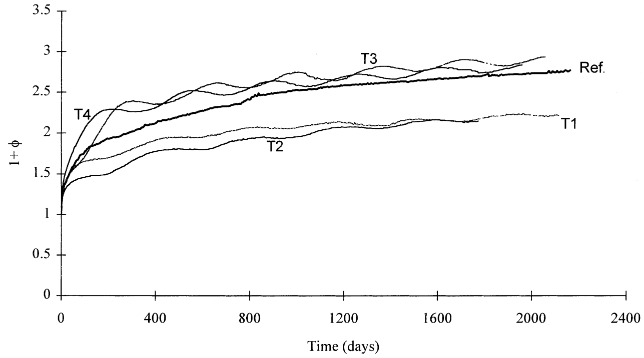

Fig. 8. Creep coefficient, ϕ, of sealed concrete – average of mixes A1, A2 and A3.

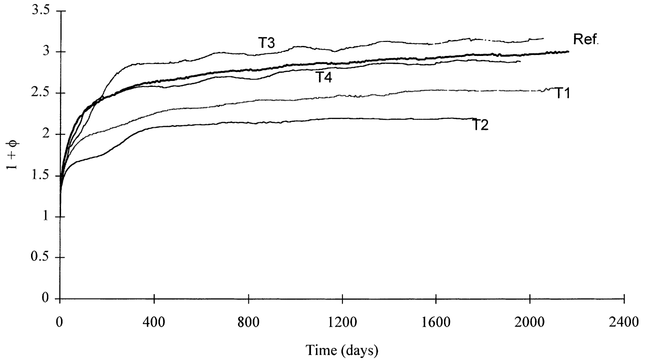

Fig. 9. Creep coefficient, ϕ, of unsealed specimens – average of mixes A1, A2 and A3.

$$\begin{aligned}&\text{when } t \approx 365 \text{ days},\\ &\text{basic creep}: \phi_{\text{summer}} < \phi_{\text{spring}} < \phi_{\text{winter}} \approx \phi_{\text{autumn}},\\ &\text{total creep}: \phi_{\text{summer}} < \phi_{\text{spring}} < \phi_{\text{winter}} < \phi_{\text{autumn}}.\end{aligned}$$

Afterwards the curves show evidence of a parallel development. The dependence of creep behaviour on 'season' may be related to the changing temperature which influences the strength development of the concrete. However, a real clear statement for the mutual position of the different curves has not yet been found.

Both for basic creep and total creep one can observe that the creep curve of the reference specimens rather leans towards the autumn and winter creep curves than to those of the spring and summer specimens.

From the test results in the present study no general valid conclusions may be drawn concerning the effect of the variation of the temperature on the one hand and that of the relative humidity on the other on the creep behaviour of concrete.

Table 2 gives the basic creep coefficient, the total creep coefficient respectively, of the different 'season'-specimens and the reference cylinders 1770 days after loading the specimens. For each season the total creep of the unsealed specimen is larger that the basic creep of the corresponding sealed specimen, and the mean ratio between $\phi_{\text{basic creep}}$ and $\phi_{\text{total creep}}$ amounts to about 0.87.

Table 2
Creep coefficient at '$t - t' = 1770$ days'

Season	$\phi_{\text{basic creep}}$	$\phi_{\text{total creep}}$	$\frac{\phi_{\text{basic creep}}}{\phi_{\text{total creep}}}$
T1	1.1646	1.5236	0.76
T2	1.1439	1.1923	0.96
T3	1.8764	2.1492	0.87
T4	1.7352	1.8911	0.92
Reference	1.6955	1.9638	0.86
Mean			0.87

4. Comparison of experimental and predicted time-dependent deformations

Two different concrete creep and shrinkage prediction models have been used, i.e., the model available in Eurocode 2 [4] and model B3 described in ACI 209 [5]. The parameters, which are taken into account in the respective models, are given in Table 3.

From Table 3, it follows that the B3-model is more complex than the EC2-model since much more parameters are involved in the B3-calculations.

The comparison between experimental and predicted shrinkage values, creep values, respectively, has been executed for the unsealed reference specimens only because both models do not predict autogenous shrinkage on the one hand and the EC2-model neither basic creep on the other. The three types of concrete (A1, A2 and A3) are considered separately here since both the concrete compressive strength and the concrete composition are variables in the models.

Besides a visual comparison of the corresponding (measured – calculated) curves also a statistical evaluation according to Bazant et al. [9] has been executed: the deviations of the model from the test data have been characterized by their coefficient of variation $\overline{w}$ which is defined for the data set number j as:

$$\overline{w}_j = \frac{1}{\overline{J}_j}\left[\frac{1}{n-1}\sum_{i=1}^{j}(w_{ij}\Delta_{ij})^2\right]^{1/2}$$

in which:

$$\overline{J}_j = \frac{1}{n}\sum_{i=1}^{n} w_{ij}J_{ij}, \quad w_{ij} = \frac{n}{n_{\mathrm{d}} - n_{\mathrm{l}}}.$$

Here J_{ij} are the measured values (shrinkage strain, 1 + creep coefficient), n the number of all data points in the data set j, Δ_{ij} the deviation of the value given by the model from the measured value, w_{ij} the weights assigned to the data points, n_{d} the number of decades on the logarithmic time scale spanned by measured data in data set number j and n_{l} is the number of data points in the decade to which point i belongs.

The overall coefficient of variation of the deviations of the model from the measured values for all data sets has been defined as:

$$\overline{w}_{\text{all}} = \left[\frac{1}{N}\sum_{j=1}^{N}\overline{w}_j^2\right]^{1/2}$$

in which N is the number of data sets.

Table 3
Variables, present in EC2- and B3-model, respectively

	EC2-model		B3-model	
	Creep	Shrinkage	Creep	Shrinkage
Mean compressive strength of concrete	X	X	X	X
Cement content of concrete	–	–	X	–
W/C ratio	–	–	X	–
Water content of concrete mix	–	–	X	X
Aggregate–cement ratio	–	–	X	–
Cement type	X	X	X	X
Effective cross section thickness	X	X	X	X
Type of specimen	–	–	X	X
Relative humidity of the ambient environment	X	X	X	X
Concrete age at loading (t')	X	–	X	–
Concrete age when drying begins (t_0)	–	X	X	X
Curing conditions	–	–	X	X

The statistics of the errors of model EC2, model B3, respectively, in comparison with the test results are given in Table 4.

4.1. Shrinkage

A comparison of predicted and observed shrinkage curves is presented in Fig. 10. The results show that:

- the measured shrinkage strains of the A2-specimen are almost equal to those of the A3-specimen. However, contrary to what someone should expect the measured shrinkage deformations of the A1-specimen (highest W/C-ratio) are continuously the smallest;
- both the EC2-model and the B3-model give good predictions for the A1-concrete at ages above 1000 days. Nevertheless, between 0 and 500 days the agreement is not good;
- the EC2-model seriously underestimates the shrinkage of the A2- and A3-concrete, respectively. Also the B3-model underestimates the observed shrinkage but the deviation between predicted and measured values is not so large as for the EC2-model at ages above 150 days;
- the predicted shrinkage trend according to the B3-model is almost the same for the A1- and A2-concretes;
- Table 4 shows that the overall coefficient of variation of the deviations of both models from the measured values is high.

Table 4
Coefficient of variation of errors (expressed as percentage) of total creep, drying shrinkage, respectively

Concrete	Shrinkage		Creep	
	EC2	B3	EC2	B3
A1	51.3	65.5	30.1	10.9
A2	53.9	58.3	24.0	12.2
A3	65.5	63.2	6.6	17.7
$\bar{w}_{\text{all}}$	57.2	62.4	22.6	13.9

4.2. Creep

In the EC2-model the creep development is described by means of 'the creep coefficient $\phi(t,t')$'; the B3-model on the other hand uses 'the compliance function $J(t,t')$'.

The creep coefficient ϕ should be calculated from the compliance function by means of the following expression:

$$\phi(t,t') = E(t')J(t,t') - 1,$$

where $E(t')$ is the static elastic modulus.

For structural analysis it is not important which equation for $E(t')$ is used, the only important aspect is that $E(t')$ and $\phi(t,t')$ together must give the correct total compliance $J(t,t') = [1 + \phi(t,t')]/E(t')$ as defined by model B3 [5].

Since it is mentioned in Eurocode 2 that the values of $\phi(t,t')$ should be associated with the tangent modulus $E_c(28) = 1.05E_{\text{cm}}$, we have used '$1.05E_{\text{cm}} = 1.05\,[9500\,(f_{\text{cm}})^{1/3}]$' ($f_{\text{cm}}$ in N/mm^2 and E_{cm} in N/mm^2) to calculate $\phi(t,t')$ from $J(t,t')$.

The curves corresponding to the predicted and measured creep coefficient are given in Fig. 11. Fig. 11 shows that:

- the trend of the creep coefficient, derived from the measured deformations, is almost the same for the A2- and A3-concretes. However, similarly to the shrinkage test results and contrary to theoretical calculations, the creep coefficient of the A1-concrete is continuously the smallest one;

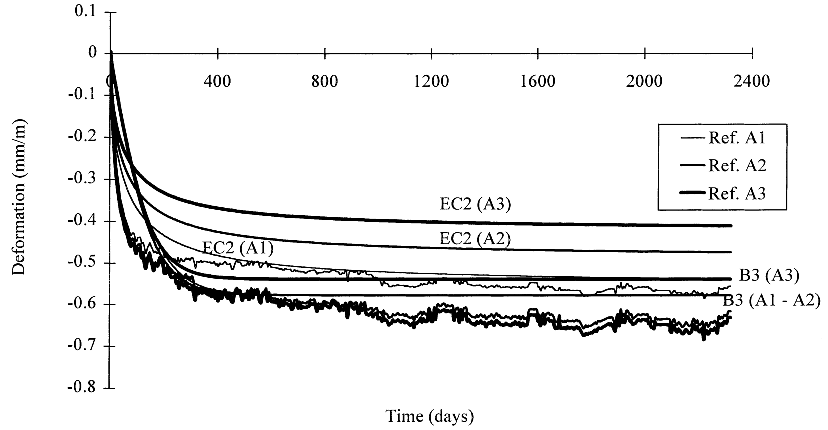

Fig. 10. Comparison of measured and predicted drying shrinkage.

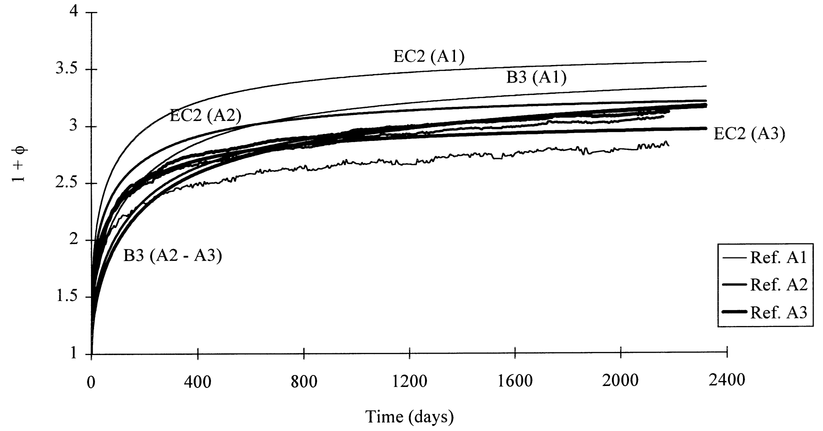

Fig. 11. Comparison of measured and predicted total creep.

- in line with the test results the B3-model predicts almost the same trend of ϕ for the A2- and A3-concrete. At ages '$t - t'$' above 500 days the similarity between measured and predicted values is extremely good. Before that age, the B3-model underestimates the creep coefficient;
- both the EC2- and B3-model seriously overestimate the creep coefficient of the A1-concrete, calculated from test results. However, the deviation of the B3-model is smaller than that of the corresponding EC2-model;
- the EC2-model predicts extremely well the ϕ-trend of the A3-concrete both in the period just after loading and at large values of '$t - t'$'. This is also confirmed by the coefficient of variation which is very small (see Table 4);
- the agreement between predicted and measured values is much better for total creep than for drying shrinkage as can be seen in Table 4. This holds for both models.

5. Conclusions

Based on the test results of the creep and shrinkage experiments carried out at variable and constant ambient conditions, the following conclusions are drawn:

1. In the present research, the effect of concrete mix on the load-dependent (creep) and the load-independent (shrinkage) deformations is negligible.
2. The influence of relative humidity on drying shrinkage is very definite.
3. From approximately one year after loading the specimen, the influence of the cyclic variation of relative humidity is not very pronounced on both total and basic creep. However, the 'season' in which the specimen was cast, seems to be important.
4. Considering the creep process there seems to be an interrelation between the effect of variable ambient humidity and changing ambient temperature. Much more experimental data are needed to be able to quantify the observed phenomena.

5. For ages '$t - t'$' above 500 days, '$t - t_0$' above 250 days, respectively, the B3-model provides in most cases better predictions both for creep and shrinkage than the EC2-model does. However, the B3-model is more complex and needs more input data.

Acknowledgements

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