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ABSTRACT: A new analytical approach to determine the ageing creep coefficient of high performance concrete under restrained autogenous deformations is proposed. The results show that changes in creep coefficient under variable stress conditions can be determined from time of setting. These changes were very high shortly after the setting time and decreased to very small changes by the age of two days. The early-age viscoelastic behavior was also found to vary with the quantity of internal curing water provided in concrete through the use of presoaked lightweight aggregate for the prevention of self-desiccation. The early-age creep coefficients determined for high performance concrete under variable stress conditions were found to be more than 50% smaller than those predicted by existing creep models mainly developed from standard compressive creep tests on normal strength concrete. Predictions of developing concrete stresses using the creep coefficients determined experimentally with the proposed approach agreed very well with measured stresses.

1 INTRODUCTION

The risk of early-age cracking in concrete structures is largely influenced by creep and shrinkage. Creep modifies the initial stress and strain patterns by increasing the load-induced deformations and relaxing the stresses due to imposed strains (Chiorino 2005). Concrete is an age-stiffening material that experiences shrinkage in any environment with a relative humidity below hygral equilibrium. Thus, autogenous shrinkage due to self-desiccation in low water-cement (w/c) high performance concrete (HPC) can be a problem. Existing creep models have been developed on concrete with w/c between 0.4 and 0.6, most of which did not experience self-desiccation, as reported by Gardner & Lockman (2001).

Internal curing with saturated lightweight aggregate (LWA) was shown to reduce self-desiccation and autogenous shrinkage of HPC by providing additional water in concrete for an improved curing and a more complete cement hydration (RILEM TC-196, 2007). Although the benefits of internal curing for HPC structures have been evidenced in laboratory studies (Weber & Reinhardt 1997) and field investigations (Villarreal & Crocker 2007), the literature offers very limited data on the visco-elastic behavior of low w/c HPC with internal curing.

This paper presents a new analytical approach to determine the basic creep coefficient of internally-cured HPC tested under restrained deformations, including initial expansion and shrinkage.

2 RESTRAINED SHRINKAGE TESTING

Four pairs of large-size HPC specimens were tested under free and restrained deformations. Four concrete mix designs were evaluated, including one reference concrete (Mix-0) with no internal curing, and three similar concretes with different levels of internal curing, namely Mix-L, Mix-M and Mix-H with low, medium and high contents of pre-soaked LWA, respectively (Table 1). This was achieved by replacing part of the normal-density sand with pre-soaked lightweight aggregate sand (e.g. expanded shale with a water absorption capacity of 15%). In this study, each concrete mix design had 450 kg/m^3 of normal cement and a total water-cement ratio of 0.34.

Table 1. Concrete mix formulations and properties.

Constituent	Quantity			
	Mix-0	Mix-L	Mix-M	Mix-H
Total water (kg)	21.3	21.3	21.3	21.3
Normal cement (kg)	62.5	62.5	62.5	62.5
Dry normal sand (kg)	125.0	117.5	110.0	100.0
LWA sand (kg, dry)	0.0	7.5	15.0	25.0
Dry coarse aggregate (kg)	125.0	125.0	125.0	125.0
Dry superplasticizer (kg)	2.1	2.5	2.1	2.7
Total w/c	0.34	0.34	0.34	0.34
Effective w/c	0.34	0.32	0.30	0.28
IC water / cement	0.00	0.02	0.04	0.06
LWA / total sand	0.00	0.06	0.12	0.20
Slump (mm)	215	210	140	102
Air content (%)	3.9	5.0	3.0	3.0
Volumetric mass (kg/m^3)	2428	2391	2420	2400
7-day strength (MPa)	50	50	54	57

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For each of the four HPC mix designs, two large-size prismatic concrete specimens (200 x 200 x 1000 mm) were prepared from the same concrete batch. Within each pair of concrete specimens, one was tested under restrained shrinkage and the other companion specimen was tested under free shrinkage. The eight concrete specimens were sealed with plastic sheets to prevent external drying shrinkage, and were tested under an ambient air temperature between 20°C and 25°C. More detailed information can be found in Cusson & Hoogeveen (2008).

Figure 1 presents the total strain measured for a period of seven days in each unrestrained concrete specimen. This measurement included autogenous shrinkage and thermal strains. It can be readily seen that the addition of pre-soaked LWA for internal curing allowed early-age expansion to occur, which was due to autogenous swelling and thermal expansion, with peaks observed between 8 to 12 hours of age. The extent of expansion increased with the quantity of pre-soaked LWA used in the concrete. Mix-H was the only concrete producing positive values of total strain after the first day until the end of testing at 7 days.

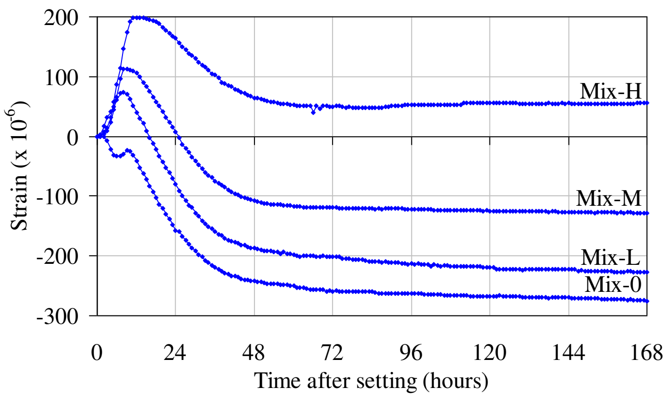

Figure 1. Total strains measured in unrestrained specimens.

The elastic strain developing over time was also determined experimentally for each of the four specimens tested under restrained shrinkage (Cusson & Hoogeveen 2008). In order to find the creep strain (ε_{cr}) as a function of time after setting (t), increments of creep strain ($\Delta\varepsilon_{cr}$) produced over a single time increment (Δt) were obtained as follows (assuming compatibility of strains):

$$\Delta\varepsilon_{cr}(t) = \Delta\varepsilon_{tot}^{R}(t) - \Delta\varepsilon_{tot}^{F}(t) - \Delta\varepsilon_{el}(t) \tag{1}$$

$$\varepsilon_{cr}(t) = \sum_{i=0}^{t} \Delta\varepsilon_{cr}(t_i) \tag{2}$$

where $\Delta\varepsilon_{tot}^{R}$ is the increment of total strain in the restrained concrete specimen (which is zero only under full restraint); $\Delta\varepsilon_{tot}^{F}$ is the increment of total strain in the unrestrained specimen (which includes non stress-induced strains due to swelling, shrinkage and thermal effects); and $\Delta\varepsilon_{el}$ is the increment of elastic strain obtained during the experiments. For example, Figure 2 presents the elastic and creep strains obtained for Mix-H concrete specimen.

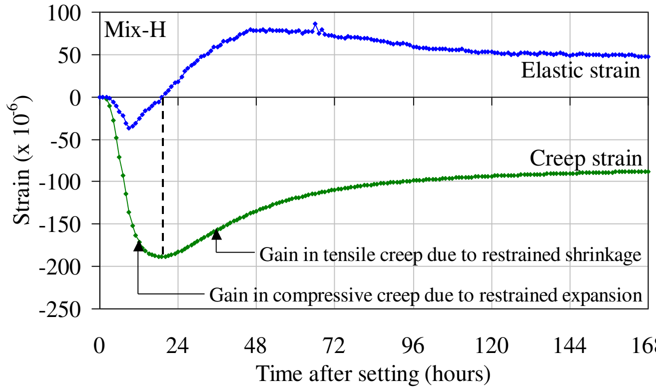

Figure 2. Measured elastic and creep strains for Mix-H.

3 DETERMINATION OF CREEP COEFFICIENT

3.1 *Pure creep or restrained shrinkage condition*

Under a constant stress, the elastic strain is also constant and the creep coefficient (ϕ) of concrete can be calculated as follows (CEB 1993; ACI 209, 1992):

$$\phi(t,t_0) = \frac{\varepsilon_{cr}(t,t_o)}{\varepsilon_{el}(t_o)} \tag{3}$$

where ε_{cr} is the creep strain measured at time t; and ε_{el} is the elastic strain applied at time of loading t_o.

Under restrained shrinkage, the elastic strain gradually increases over time, and the conventional definition of the creep coefficient (Eq. 3) cannot be used. In this case, the following definition was proposed by Kovler (1994):

$$\Omega(t)\phi(t) = \frac{\varepsilon_{cr}(t)}{\varepsilon_{el}(t)} \tag{4}$$

where Ω is the ageing factor, which accounts for the fact that ε_{el} is not constant but applied gradually. For simplicity, engineers have often used a constant value of 0.8 as an approximation (CEB 1993). In this paper, reference to the ageing creep coefficient as ϕ will imply that the effect of Ω is included.

3.2 *Restrained expansion/shrinkage condition*

In the more general case of restrained expansion followed by restrained shrinkage, the elastic strain changes over time and can be negative (compressive) under restrained expansion and positive (tensile) under restrained shrinkage. As shown in Figure 2, under an initial restrained expansion, the negative elastic strain produced an increase in compressive creep strain. The compressive creep strain reached a peak value of -190×10^{-6} when the elastic strain reduced to zero before changing into a restrained shrinkage mode.

As the tensile elastic strain increased (or remained in the positive range), positive increments of creep strain were produced and resulted in less negative values of creep strain (e.g. –90 x 10^{-6} at 7 days). In this case, Equation 4 does not apply and will result in negative values of ageing creep coefficient after the stress reversal from compression to tension.

In order to determine the ageing creep coefficient in this case, it is proposed to define the increment of ageing creep coefficient ($\Delta\phi$) as follows:

$$\Delta\phi(t) = \frac{\Delta\varepsilon_{cr}(t)}{\varepsilon_{el}(t)} \tag{5}$$

where $\Delta\varepsilon_{cr}$ is the increment of creep strain at time t produced by the full elastic strain (ε_{el}) applied at time t. With Equation 5, the signs of $\Delta\varepsilon_{cr}$ and ε_{el} will always match, resulting in a gradually increasing ageing creep coefficient over time, which can then be determined incrementally as follows:

$$\phi(t,t_o) = \sum_{i=t_o}^{t} \Delta\phi(t_i) \tag{6}$$

Substituting Equation 5 into Equation 1, and taking $\Delta\varepsilon_{cr}(t) = \varepsilon_{cr}(t) - \varepsilon_{cr}(t\text{-}\Delta t)$, the elastic strain applied at time t was found to be:

$$\varepsilon_{el}(t) = \frac{\varepsilon^{R}_{tot}(t) - \varepsilon^{F}_{tot}(t) - \varepsilon_{cr}(t-\Delta t)}{1+\Delta\phi(t)} \tag{7}$$

which can be solved using an incremental procedure. In Eq. 7, $\Delta\phi$ was determined experimentally by conducting a linear regression analysis on the test data. For this, the following power equation was used:

$$\Delta\phi(t) = At^{B} \tag{8}$$

where A and B are best-fit parameters determined by minimising the sum of absolute differences between the experimental values of creep strain and the fitted values of creep strain obtained by using the modelled values of elastic strain (Eq. 7) into Equations 1-2. Figure 3 presents the measured and best-fit creep strains obtained for the tested HPC specimens.

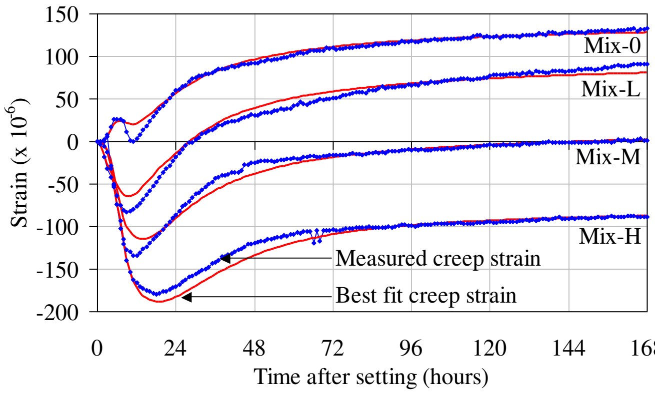

Figure 3. Measured and best-fit creep strains.

The resulting best-fit curves for the increments of creep coefficient ($\Delta\phi$) as a function of time are illustrated in Fig. 4 for the different concrete specimens. As expected, it can be observed that the increments of ageing creep coefficient can be very large at very early ages and very small after an age of two days (at which time the elastic modulus of concrete reached 90% to 95% of its ultimate value). Ozawa & Morimoto (2002) also found major differences in creep coefficients measured for loading times before and after the age of 2 days.

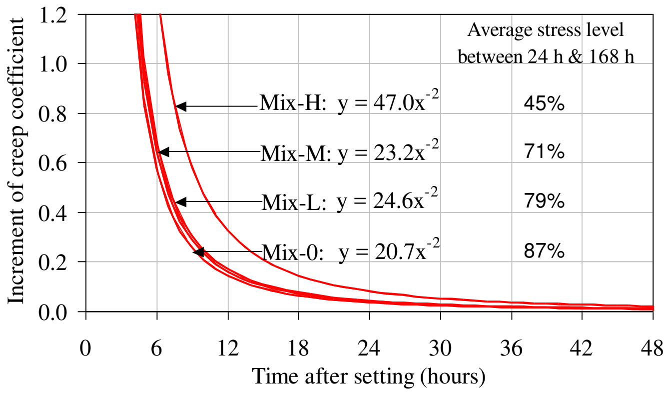

Figure 4. Best-fit increments of ageing creep coefficient.

Using Eq. 6 (ϕ) and the empirical relationships shown in Fig. 4 ($\Delta\phi$), the ageing creep coefficients were determined as functions of time after setting (t) for 28 days and for arbitrary loading times of 0.5, 1, 2, 3, 4, 5, and 7 days. It is interesting to note that this approach only requires one set of specimens to obtain $\phi(t,t_o)$ corresponding to different loading ages.

Figures 5-8 present the obtained ageing creep coefficients for the four HPC specimens, respectively. It can be observed that the ageing creep coefficients at very early ages increased very rapidly, especially when the loading ages were 0.5 day and 1 day. This effect is even stronger for Mix-H specimen as shown in Figure 8, where a high value of 3.7 was found for $\phi(28,0.5)$, compared to 1.6 for the reference concrete specimen with no internal curing.

The 28-day values of ageing creep coefficient reported in Figures 5-8 are not ultimate values, but could be considered as being close to ultimate values since the slopes of the curves at the age of 28 days are very small and because drying creep in this study can be considered negligible due to the sealed condition used during testing. Reported ultimate values of creep coefficient varied from 0.92 to 2.46 for high-strength concrete (Huo et al. 2001), and from 1.3 to 4.2 for normal strength concrete (ACI 209, 1992). Note that these reported values are mostly representative of concrete specimens tested under drying conditions and loaded with a constant compressive force at the age of 7 days, which makes the comparison with the present test results difficult.

In order to compare the results of this study, three established creep models were used to predict the creep coefficient for the HPC specimens. They are the GL2000 model developed by Garder & Lockman (2001), the ACI 209 (1992) model, and the CEB MC90 (1993) model. In order to simulate the test conditions used in this study, a concrete relative humidity of 96% (sealed curing) and a 28-day concrete strength of 60 MPa were assumed in these creep models. Figure 9 presents the creep coefficients predicted by the GL2000 for loading times of 0.5, 1, 2, 3, 4, 5 and 7 days, and those predicted by the ACI and CEB models for a 7-day loading time.

When comparing the experimental results in Figures 5-8 with the predicted values of creep coefficient in Figure 9, one can observe some similarities and several differences in the 28-day values of creep coefficient and in its development rate. For instance, for the very early loading times of 0.5 day and 1 day, the time development of ϕ for Mix-H specimen is similar to the predictions of the GL2000 model. For loading times equal to or greater than 2 days, the creep coefficients for the four HPC specimens are more than 50% smaller than the predictions from the GL2000 model. The same observation applies when comparing the experimental values of the creep coefficient with the predictions obtained using the ACI and CEB models for a loading time of 7 days.

These differences can be attributed to factors like loading/curing conditions, and concrete mix design. For instance, the existing creep models were based on large sets of results, most of which were obtained from compressive creep testing of normal strength concrete under drying conditions.

In the present study, the elastic strain was applied gradually under restrained expansion (compressive creep/relaxation) for less than a day and then under restrained shrinkage (tensile creep/relaxation) for the remaining time. Under nearly full restraint conditions, the elastic strain reached values near the ultimate strain capacity of the concrete, which is different from standard creep testing, in which the specimens are usually loaded to 40% (or less) of the available concrete strength. In reality, creep of concrete is a non-linear phenomenon (CEB 1993). Non-linearity with respect to creep may be observed in experiments where the sustained stress is higher than 40% of concrete strength, or in experiments with variable stress history.

Sealed curing and different levels of internal curing were used in this study, thus eliminating the component of drying creep. Also, most of the concrete specimens tested for creep in the literature had water-cement ratios between 0.40 and 0.60. Consequently, the existing creep models cannot capture the effect of self-desiccation in low water-cement high-strength concrete.

In light of the above, the good agreement of the measured creep coefficients for Mix-H concrete at the 0.5-day loading age may be explained by: (i) very effective internal curing, which prevented self-

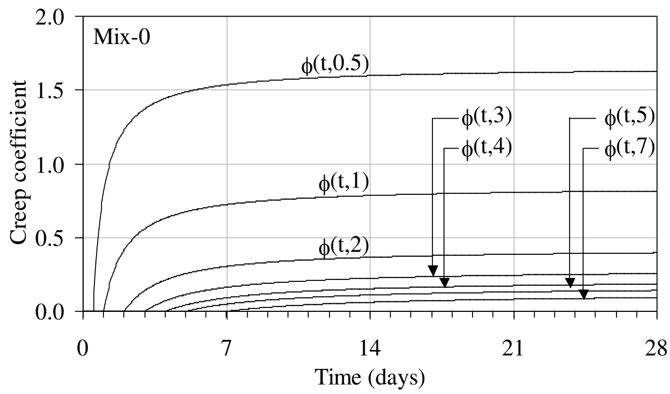

Figure 5. Ageing creep coefficients for Mix-0 specimen.

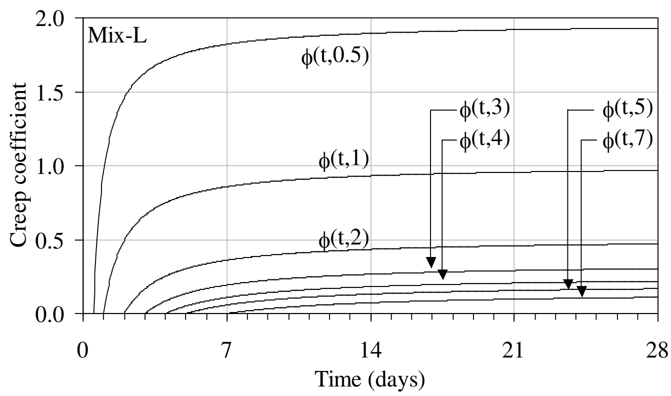

Figure 6. Ageing creep coefficients for Mix-L specimen.

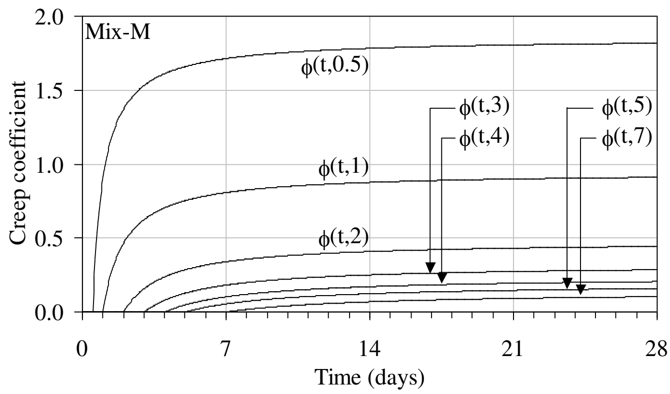

Figure 7. Ageing creep coefficients for Mix-M specimen.

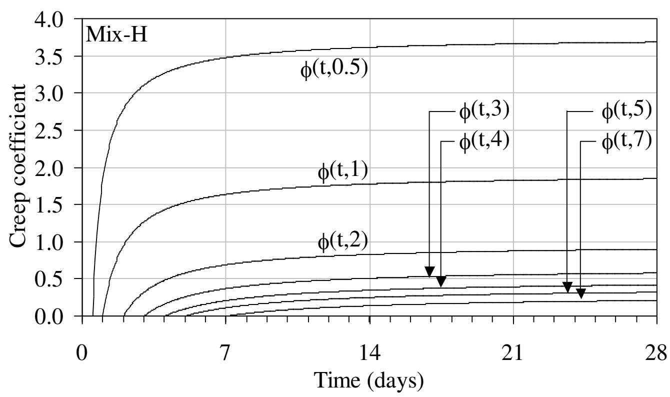

Figure 8. Ageing creep coefficients for Mix-H specimen.

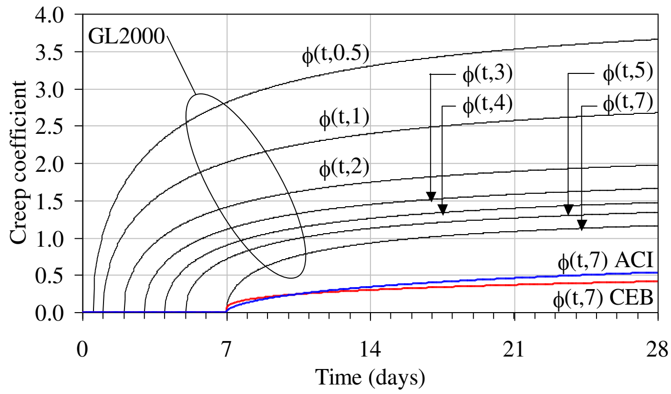

Figure 9. Predicted creep coefficients from existing models.

desiccation at early ages as the measured internal concrete RH remained above 96% for the seven days of testing; and (ii) the lower average applied stress level of 0.45, which is not far from the 40% limit, under which creep strains are assumed to be proportional to sustained stresses (ACI 1992, CEB 1993).

4 PREDICTION OF CONCRETE STRESSES

Using the proposed calculation approach, the concrete stress (σ_c) in the HPC specimens resulting from restrained expansion/shrinkage was simply calculated as follows:

$$\sigma_c(t) = E_c(t)\,\varepsilon_{el}(t) \tag{9}$$

where E_c is the concrete modulus of elasticity at age t; and ε_{el} is the elastic strain calculated at age t with the proposed Equation 7.

In order to verify the validity of the present approach (i.e. using Equations 5-9), the conventional approach suggested by CEB (1993) was also used to determine the concrete stress developing over time in the four HPC specimens as a result of restrained expansion/shrinkage. Considering that concrete complies with the theory of linear visco-elasticity of ageing materials (Bažant 1975, 1995), the following equations based on the principle of superposition were used (CEB 1993):

$$\sigma(t,t_o) = \int_{t_o}^{t} R(t,\tau)\, d\varepsilon_{tot}^{R}(\tau) \tag{10}$$

$$R(t,t_o) = E_c(t_o)\left[1 - \frac{\phi(t,t_o)}{E_c / E_c(t_o) + \Omega(t_o)\cdot\phi(t,t_o)}\right] \tag{11}$$

where R is the relaxation function, which represents the axial stress produced at time t by a constant unit strain applied at time t_o; $E_c(t_o)$ is the concrete modulus of elasticity at time t_o; E_c is the concrete modulus of elasticity at 28 days; Ω is the concrete ageing coefficient (set to 0.8); and ϕ is the creep coefficient, which was obtained experimentally for the HPC specimens using the proposed approach (Figures 5-8). Equation 10 was numerically solved using an incremental procedure.

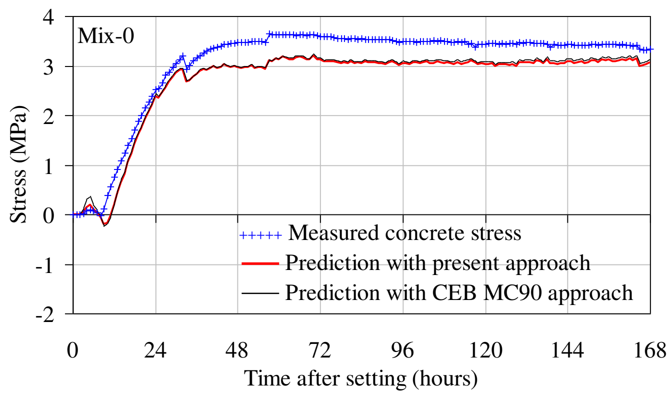

Figure 10. Stress predictions for Mix-0 concrete specimen.

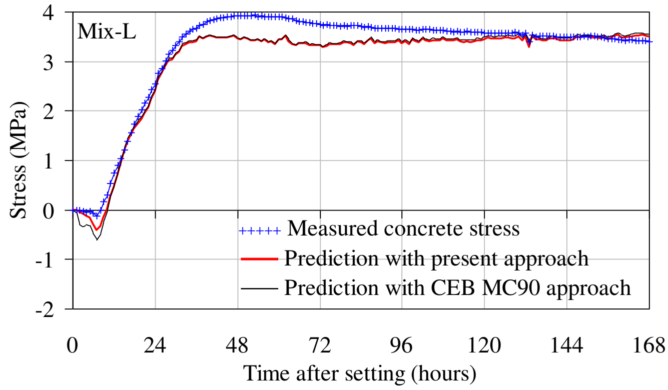

Figure 11. Stress predictions for Mix-L concrete specimen.

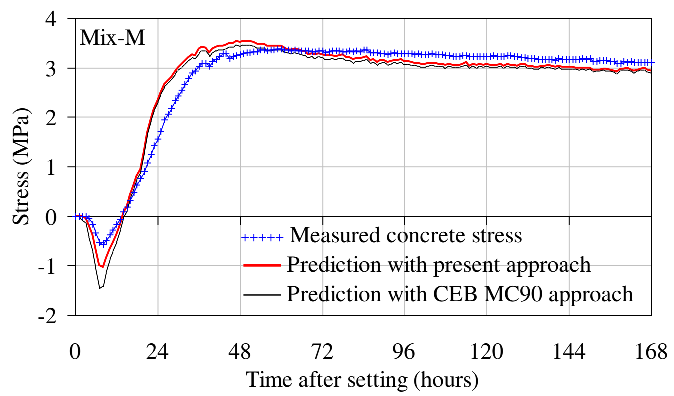

Figure 12. Stress predictions for Mix-M concrete specimen.

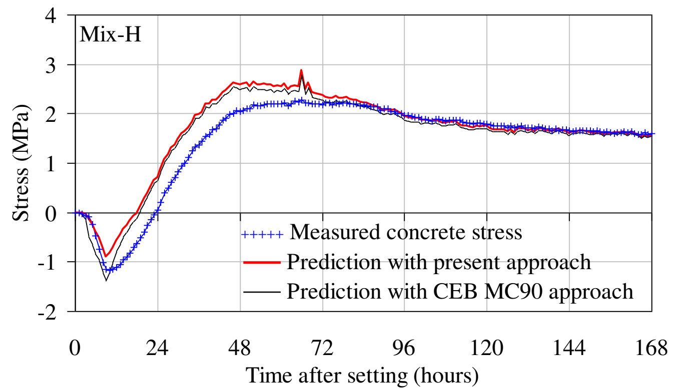

Figure 13. Stress predictions for Mix-H concrete specimen.

The stress predictions from both the proposed and conventional approaches are compared to the experimental stress results for the four HPC specimens in Figures 10-13. Both stress calculation approaches (using the same sets of creep coefficients) provided nearly identical stress predictions over the 7-day test period. The predictions also agreed very well with the test results for the HPC specimens. It is noted that the CEB approach, assuming linear viscoelasticity, also provided excellent stress predictions for specimens tested under high stress levels. This is because the relations for the creep coefficient increment (Fig. 4) captured the nonlinear creep effects.

For Mix-L and Mix-M, it can be observed that the very early age compressive stresses were slightly overestimated during the restrained expansion phase, which occurred within the first 12 hours after setting. This may be explained by the fact that the linear regression analysis of the creep data was conducted on the entire set of data obtained from time of setting to the age of 7 days, as opposed to performing the analysis in two separate steps (i.e. restrained expansion vs. restrained shrinkage). Nevertheless, the predictions of the present approach using the best-fit relations shown in Fig. 4 agreed nicely with the experimental values of creep coefficient.

5 SUMMARY AND CONCLUSIONS

A new analytical approach is suggested to determine the ageing creep coefficient of low water-cement high performance concrete under uniaxially restrained autogenous deformations, including initial expansion followed by shrinkage. The following conclusions can be drawn from this study:

1. Determining creep coefficient under restrained shrinkage with the present approach requires one set of specimens to obtain $\phi(t,0)$, and all subsets $\phi(t,t_o)$, for a given concrete and environment.
2. The increments of creep coefficient under variable stress conditions were determined from the time of setting, showing very high creep rates shortly after setting compared to later ages (two days), after which time the creep rates were found to be very small (drying prevented).
3. Increasing levels of internal curing in HPC resulted in larger compressive creep developing at early ages due to larger restrained expansion, which is excellent for reducing the cracking risk.
4. The creep coefficients of HPC determined under the present test conditions (i.e. restrained autogenous deformations, high stress levels, internal curing) were found to be more than 50% smaller than those predicted from existing creep models (GL2000, ACI, CEB) that are mainly based on compressive creep test results from normal strength concrete specimens.
5. Predictions of developing concrete stresses in the HPC specimens using the creep coefficients determined with the proposed approach agreed well with measured concrete stresses.
6. Predictions of concrete stresses with the proposed simple approach were nearly identical to those obtained with the conventional CEB model, when both approaches used the experimentally determined creep coefficients, which also captured the nonlinear creep effects.

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