Upper and lower bounds for the elevated temperature creep of hardened cement paste

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1 INTRODUCTION

The creep of cement paste and concrete at elevated temperatures will vary in magnitude, depending on a multiplicity of external and internal factors. In order to quantify this behaviour for use in structural creep analysis, one should seek first to model the upper and lower bound creep responses, from which it may be attempted to interpolate intermediate responses.

The upper bound for creep, known as "transient thermal creep", takes place when load is applied during the first time heating of concrete. The lower bound for creep, known as "basic creep", will take place only when thermal, hygral, chemical and dimensional equilibrium have been achieved at a given temperature before the load is applied. Although transient thermal creep has been researched fairly extensively (1), much of the research on constant temperature creep has not met the criteria for it to be called basic creep.

Hardened cement paste (OPC) was used for this investigation in place of concrete, because variability due to aggregate type was thereby avoided and also because cement paste is in fact the creeping medium in concrete.

2 CRITERION FOR OBTAINING THE LOWER BOUND RESPONSE

The creep response at elevated temperature for unsealed cement paste will depend on the point of loading, which may vary as in Figure 1. Loading at point A, the start of the temperature rise, would result in the measured strains comprising transient creep (which includes drying creep), shrinkage and thermal expansion. If loading is applied at the end of the temperature rise, at point B, the measured strains may still contain drying creep and shrinkage, in addition to creep and shrinkage components due to incomplete internal stabilization. For the creep strains to be free of these components, the load must be applied at point D or thereafter, i.e. after dimensional stability has been achieved. Figure 2 shows the differences in the 1-day creep strain for loading at some point C, compared to loading at point D, for specimens at 300,425 and 525°C. It also shows that the creep response is the same, whether the load is applied at point D, or any point E after this time, for specimens at 300, 400, 425 and 600°C. Hence, applying the load at point D or thereafter, i.e. after the achievement of dimensional stability, would result in the lower bound creep response. This can therefore strictly be called "basic creep", and defined as the load-induced time-dependent deformation of a specimen which is loaded after achieving thermal, hygral, chemical and dimensional equilibrium at first heating to a given temperature.

The time taken to reach dimensional stability at a given constant temperature was found to vary with temperature level, depending on the extent and rate of the internal transformations taking place at the given temperature. Unloaded cement paste specimens at around 50°C and 400-460°C took several weeks to stabilize, due to slow desorption of evaporable water and slow dissociation of calcium hydroxide respectively.

3 EXPERIMENTAL DETAILS

The details of the creep test apparatus (2) and the conduct of the tests (3) are described elsewhere. The specimens were made of OPC paste having a water/cement ratio of 0.3, cured at 100% RH and 20°C for 14 weeks and kept at 60% RH and 20°C thereafter. They were tested at ages between 14 and 28 weeks, over which period their strength was constant at 99 N/mm^2. The stress/cold strength ratio employed in the creep tests was 0.11.

The transient thermal creep tests were performed by loading the specimens prior to heating. The transient thermal creep strains were obtained by deducting corresponding shrinkage strains (measured in concurrent tests) from the strains measured under load. In the basic creep tests, the loading was performed after dimensional stability was achieved at temperature. The rate of heating for both series of tests was 1°C/min.

4 TIME FUNCTIONS FOR TRANSIENT THERMAL AND BASIC CREEP

The differences between the transient thermal and basic creep responses were marked. Not only were the transient thermal creep responses much greater than the basic creep ones, but they were also different in their form of time dependence, tending to level out after a few days.

The time function for upper bound creep was best represented by the formula $\varepsilon_c = P\,(1-e^{-qt})$ for times from 0.01 days to 18 days, at temperatures from 50°C to 300°C. The parameter P increases with increasing temperature, while the constant q reduces in general with increasing temperature, as seen in Figure 3.

The time function for basic creep was best represented by the power law formula $\varepsilon_c = At^n$ for times from 0.001 days to 40 days, at temperatures from 20°C to 670°C. This is in agreement to the findings of other researchers (4,5). An indication of the closeness of fit can be obtained from Figure 4, for specimens at three temperatures, loaded for 40 days. The parameter A gives the creep strain at unit time, while the constant n is but mildly dependent on temperature, taking an average value of 0.36 (6).

If the specimen is loaded at a time in between the points that give rise to transient thermal and basic creep, the ensuing creep response will also be an intermediate one between the upper and lower bounds, both with respect to magnitude and time function. This is shown in Figure 5 for a specimen loaded soon after reaching a maximum temperature of 120°C. The intermediate point response has been fitted by both the upper and lower bound formulae, keeping the values of the exponents q and n unchanged. Thus the intermediate response with time is modelled in forms that bear constant ratios to the upper and lower bound responses.

5 THERMAL LOADING OF STRUCTURALLY INDETERMINATE SYSTEMS

Consider the situation where a structurally indeterminate system is subjected to a gradually applied thermal load. A macro-level example of such a system would be an indeterminate concrete framed structure; a meso-level example would be the aggregate-paste system that comprises the concrete material itself. In both these cases, stresses will be produced as a result of differential thermal movements. However, these stresses will be relieved to an extent due to the creep exhibited, in the one case by the concrete as a whole and in the other case by the cement paste matrix.

Apart from inducing stresses in an indeterminate system, the gradually applied thermal load will also cause a continuous change in the moisture condition of the creeping medium. Therefore the continuously unfolding stress history imposed by the gradually applied thermal load will give rise to a spectrum of continuously changing creep responses. In fact, if the material was initially in a moist, unsealed state, it would experience the entire range of creep curves, from transient thermal to basic.

This problem can be solved by considering the continuous spectrum of responses as a series of affine creep curves, after discretizing the duration of thermal loading into suitable time steps. This approach is similar to the well known adjustment of creep response for age (7), where an age-adjustment factor (in value less than unity) is used as a multiplier on the initial creep curve, in order to obtain the diminishing affine curves.

In our case, the variation of this multiplier with time can be obtained by using the upper and lower bound responses, together with one or more intermediate point responses. In the following example, the creep corresponding to 120°C has been studied, using just one intermediate response as shown in Figure 5. Since this has been modelled to bear a constant ratio to both the upper and lower bound responses, the ratios of all three responses to each other can be obtained. A hyperbolic function has been fitted through these ratios to obtain the $\alpha(\tau)$ curve in Figure 6. Hence, the creep compliance for any time of loading, τ, can be written as

$$J(t,\tau) = \alpha(\tau)\ J_1(t-\tau,0)$$

where J_1 is the upper bound creep compliance, modelled as an exponential-type expression, and t is the time from initiation of heating.

After some point in time, τ', the creep compliances will be closer to a power law expression rather than an exponential one. Hence, in the example here, a $\beta(\tau)$ curve (Figure 6) has been obtained, giving the ratios of subsequent creep responses to the intermediate point response, modelled by a power law expression. The curve has been made affine to the $\alpha(\tau)$ curve.

Thus, the creep compliance for any time of loading, $\tau \geqslant \tau'$, can be written as

$$J(t,\tau) = \beta(\tau)\quad J_2(t-\tau,\tau')$$

where J_2 is the intermediate point creep compliance, modelled as a power law expression.

Therefore, if t is the time from initiation of gradual heating and τ' is the time at which the creep response is deemed to change from an exponential-type to a power law expression, the creep compliance for any time of loading τ, can be written as

$$J(t,\tau) = \alpha(\tau)\ J_1(t-\tau,0) \qquad 0 \leqslant \tau < \tau'$$

$$= \beta(\tau)\ J_2(t-\tau,\tau') \qquad \tau \geqslant \tau'$$

The stress analysis problem may then be solved, using a suitable method of structural creep analysis.

6 CONCLUSIONS

- The upper and lower bounds for the creep of unsealed hardened cement paste at elevated temperatures differ markedly, not only in magnitude but also in their form of time dependence.
- The lower bound creep response of unsealed hardened cement paste, known as "basic creep", will be obtained only if thermal, hygral, chemical and dimensional equilibrium have been achieved at a given temperature before the load is applied.
- The gradual thermal loading of an unsealed structurally indeterminate concrete system will cause a continuously unfolding stress history and result in a continuum of creep responses from transient thermal to basic. This problem can be solved by discretising these creep responses into a series of diminishing affine creep curves.

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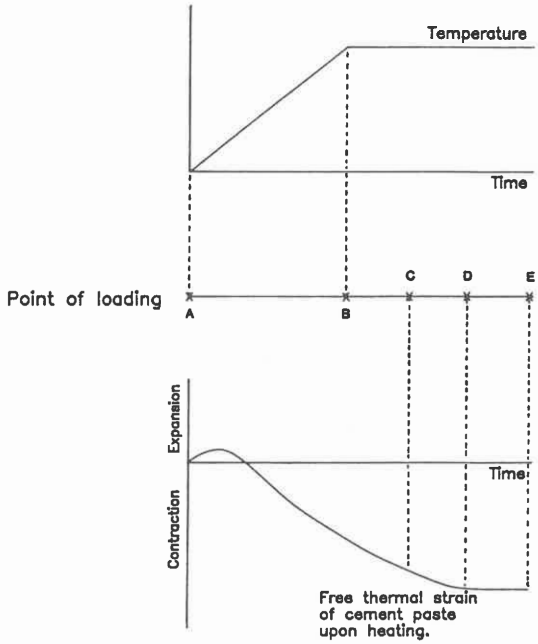

Figure 1 - Various options for loading a cement paste specimen subjected to gradual heating.

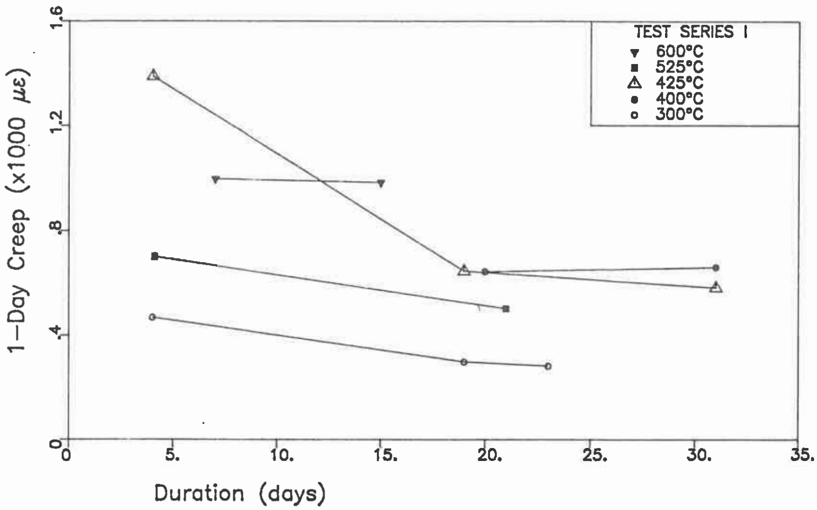

Figure 2 - Effect of preheating duration on the subsequent 1-day creep strain of hardened cement paste.

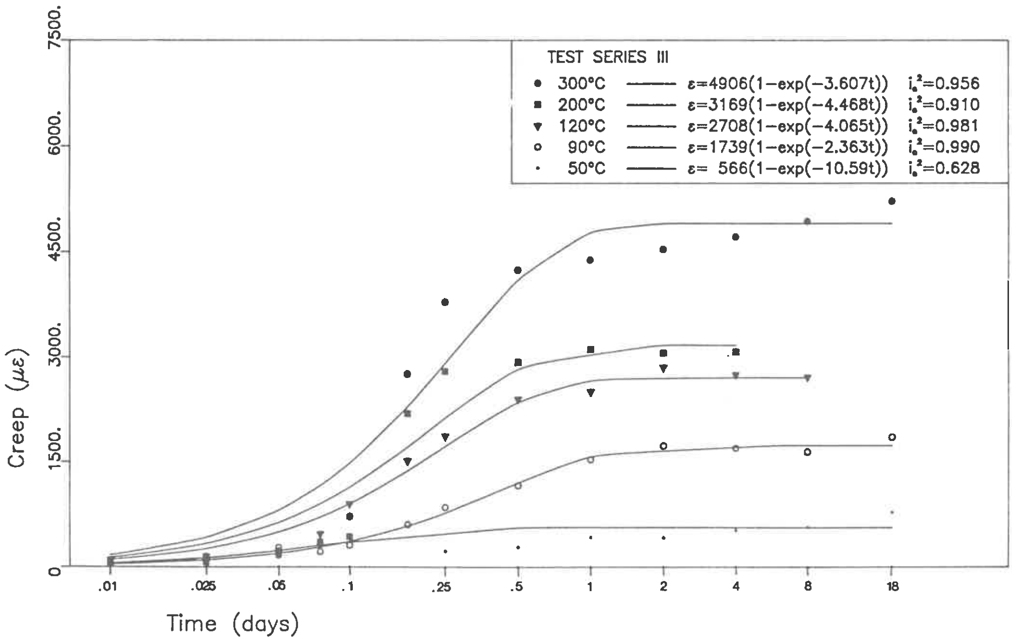

Figure 3 - Transient thermal creep strains fitted by exponential law.

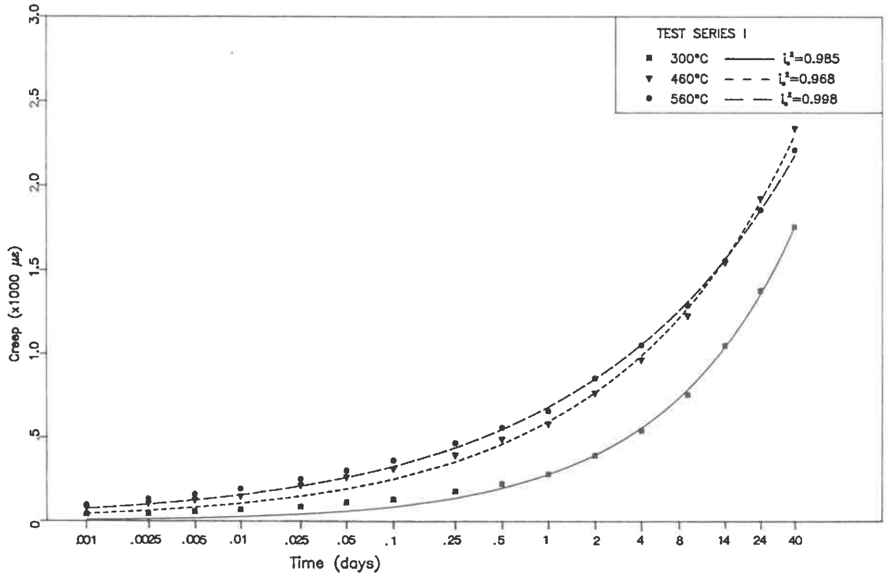

Figure 4 - Basic creep strains fitted by power law expressions.

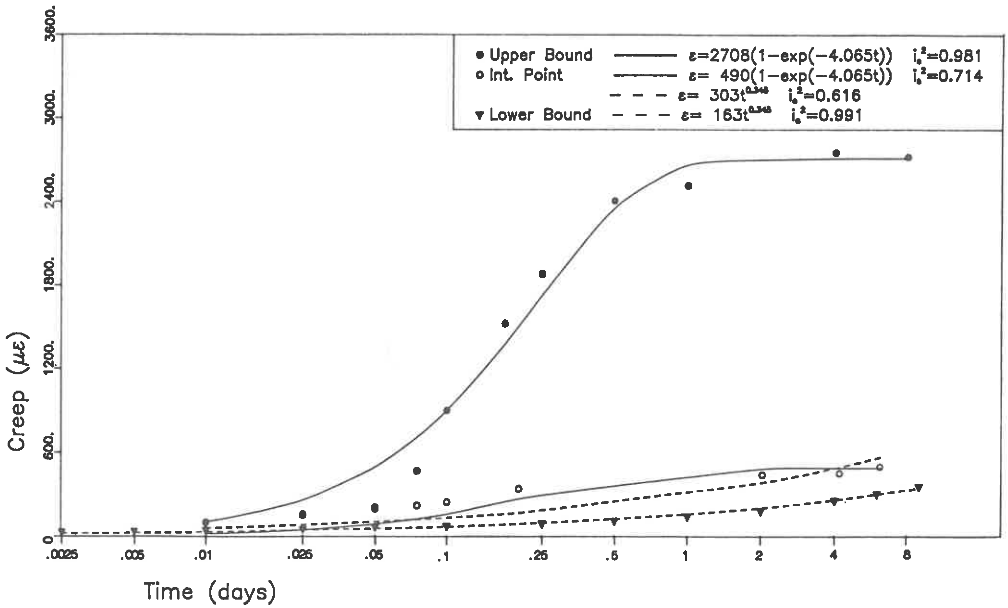

Figure 5 - Upper bound, lower bound and intermediate point creep responses corresponding to a maximum temperature of 120°C.

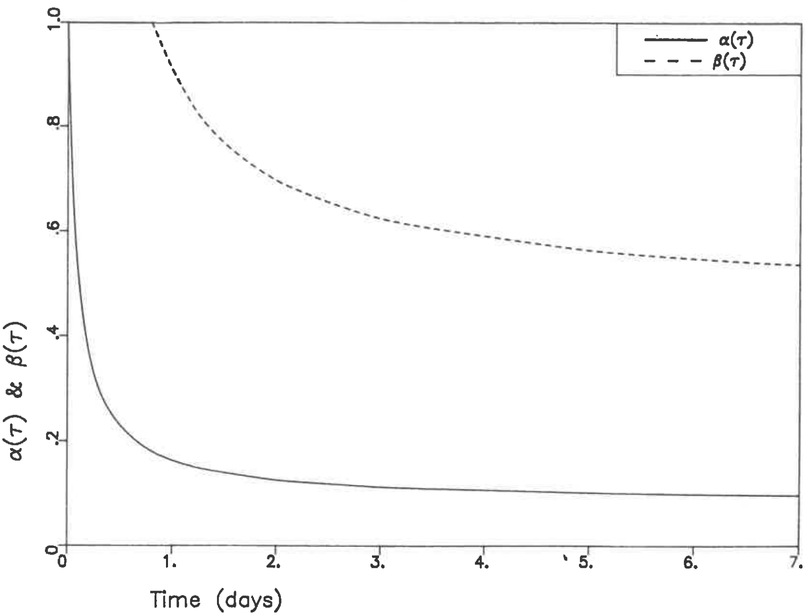

Figure 6 - Factors to account for diminishing creep response with duration of heating prior to loading.