Viscoelastic Creep of High-Temperature Concrete

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Abstract

Presented in this report is the analytical model for analysis of high temperature creep response of concrete. The creep law used is linear (viscoelastic), the temperature and moisture effects on the creep rate and also aging are included. Both constant and transient temperature as well as constant and transient moisture conditions are considered. Examples are presented to correlate experimental data with parameters of the analytical model by the use of a finite element scheme.

1. Introduction

The knowledge of concrete behavior at high temperature is important in nuclear reactor safety considerations. It has been postulated that structural concrete could be exposed to very high temperatures, which may result from hot reactor coolant or even core debris coming in direct contact with the concrete. Under these conditions the integrity of concrete and thus the reactor containment is subject to the question; how safe is the reactor containment under such severe environmental conditions?

Modeling of concrete creep and shrinkage at temperatures over 100°C is of particular interest for finite element analysis of accident situations in nuclear reactor structures. Experimental results indicate that creep of concrete accelerates at high temperatures. The effect of high temperature creep on the structure may cause extensive redistributions of stresses which, along with shrinkage and thermal dilatation, may lead to damage of the containment.

Although some experimental work has been generated in the high-temperature response of concrete [1], much more research remains to be done. Concurrently, the need of structural analyses to predict containment response persists. The purpose of this paper is to describe an approximate constitutive model for creep and shrinkage of concrete at temperatures up to about 400°C. While important nonlinear effects on deformations certainly exist above 100°C, a linear formulation of creep will be assumed as a first order approximation.

The response of concrete at high temperatures cannot be calculated without the knowledge of the changes in the moisture content and its distribution, as well as the pressure of the pore water. Moisture content and pore pressure calculations have been formulated and developed elsewhere and are available in the finite element program TEMPOR2 [2]. This program can handle the temperature, moisture distribution and pore pressure calculations of concrete for temperatures up to 800°C. Thus, the information from this program can be used in the structural analysis performed by the nonlinear finite element program STRAW [3].

The total strain, ε, of concrete at high temperature can be subdivided into three components:

$$\varepsilon = \varepsilon^{M} + \varepsilon^{T} + \varepsilon^{H} \tag{1}$$

where ε^M is the mechanical strain (strain caused by stress), ε^T is the thermal dilatation, and ε^H is the hygral strain (strain caused by moisture changes, either shrinkage or swelling).

The creep law is assumed to be linear, i.e., it follows the principle of superposition. The linearity assumption is acceptable for concrete stressed to less than about one-half of its compressive strength. Thus, if the stress, σ, is assumed to be constant,

$$\varepsilon^{M} = \sigma\, J(t,t') \quad ; \quad J(t,t') = \frac{1}{E_0} + \frac{g(\hat{w})\,\phi_T f_w}{E_0}\, \phi_1 \left(t_e'^{\,-m} + \alpha\right) \left(t-t'\right)^{n} \tag{2}$$

in which $J(t,t')$ is the compliance function (also called creep function) that represents the strain at age t caused by a unit stress that has been acting since age t'. At variable moisture content, w, and variable temperature, T, the compliance function may be approximated by the double power law as given in Eq. (2), where E_0 is the asymptotic modulus (~1.5 times the conventional elastic modulus for 28 day old concrete); m, n, α and ϕ_1 are parameters for a given concrete, t is the current time (days), t' is the time of loading, t_e' is the equivalent hydration time, ϕ_T is a function of temperature, f_w is a function of moisture content and $g(\hat{w})$ is function of moisture rate and strain rate. Detailed explanations of the functions t_e', ϕ_T, f_w, and $g(\hat{w})$ are given in Ref. [4].

Thermal and hygral strains, including stress dependency, may be calculated [5,6] by:

$$\varepsilon^{T}_{ij} = \int_{T_0}^{T} \alpha_T \left(\delta_{ij} + \beta\sigma_{ij}/f_c'\right) dT \quad ; \quad \varepsilon^{H}_{ij} = \int_{w_1}^{w} k_s \left(\delta_{ij} + \beta\sigma_{ij}/f_c'\right) dw \tag{3}$$

where δ_{ij} is Kronecker delta, α_T is the thermal dilatation, T_0 is the initial temperature, k_s is the shrinkage coefficient, w_1 is the initial moisture content, σ_{ij} is the stress tensor, β is a dimensionless material constant, and f_c' is the compression strength of concrete. Note that if $\beta = 0$, only volumetric thermal and hygral strains would occur. It may also be noted, that, as shown in Ref. [5], stress induced shrinkage and thermal dilatations represent a special, simplified case of a more general thermodynamic theory for behavior of concrete due to its two-phase nature [7].

To generalize the preceding formulation to time-variable stresses (because of possible variation of applied loads and creep itself), one can proceed under the assumption of linearity and determine an equivalent rate-type formulation. The Maxwell chain unit is used in the rate-type formulation, and along with t_e', ϕ_T, f_w, and $g(\hat{w})$ and Eqs. (1-3), the approximate constitutive relation for creep is defined. Efficient numerical algorithm for a step-by-step solution of these equations have been previously presented [8].

2. Numerical Studies

Marechal [9] conducted tests on creep properties of concrete subjected to different temperature. One of the tests performed was on concrete that had been dried at 105°C for a period of one month. The specimen size was a 7 x 7 x 28 cm prism and was cured for one year at 20°C and 100% relative humidity. A number of tests were done at 20, 70, 105, 150, 250 and 400°C with a uniaxial load of 10 MPa. Loading was imposed after the concrete was dried at 105°C; the test temperature was applied slowly (0.25°C/hour) and once the test temperature was reached it was held for two weeks; next the axial load of 10 MPa (approximately 20% of the compressive strength at 20°C) was applied. The results of the creep test are shown in Fig. 1, with the creep deflection difference between 100 days and ten days $(\Delta_{cr(100)} - \Delta_{cr(10)})$ versus test temperature. Material properties of the dried concrete at 20°C are: Young's Modulus, $E = 27500$ MPa (4.0×10^6 psi), and Poisson's ratio, $\nu = 0.18$.

The problem was analyzed using one axisymmetric finite element to approximate the test specimen. Since the concrete was dried at 105°C, it was assumed that only the function ϕ_T will be needed because the other functions, $g(\hat{w})$ and f_w, involve moisture changes. By fitting the creep data for 20°C (reference temperature for which $\phi_T = 1$) the constants in Eq. (2), were $E_0 = 8.0 \times 10^6$ psi (55200 MPa), $\phi_1 = 10.69$, $t' = 400$ days, $m = 0.33$, $\alpha = 0.05$ and $n = 0.09$. The best fit of Marechal's data was found by setting $U_a/R = 4000$°K for ϕ_T (U_a = activation energy of creep, R = gas constant); the results are shown in Fig. 1. The value of $U_a/R = 3700$°K was estimated by Marechal [9] in his analysis.

Anderberg and Thelanderson [6] performed creep tests on concrete subjected to a constant, stabilized temperature. A constant load was applied after the actual test temperature was reached and sustained for three hours in order to measure creep. The cylindrical test specimen size was 7.5 cm in diameter and 15.0 cm long, see Fig. 2; it was cured 21 weeks at 20°C and 65% relative humidity. Numerous tests were done at 20, 130, 200, 300, and 400°C with a uniaxial compressive load of 9.65 MPa (approximately 23% of compressive strength at 20°C). The temperature was applied at 5°C/min until the desired temperature was reached and then held constant for a total combined time of three hours. For each test temperature, unloaded comparison specimens were tested to obtain the volume change (e.g. shrinkage) at the same temperature. There was no observed measurable deformation on these specimens during the time period corresponding to the creep test (three hours). The results of the creep test are shown in Fig. 2, as the creep strain at three hours versus test temperature. Material properties of the concrete at 20°C are: Young's Modulus, $E = 25800$ MPa (3.742×10^6 psi), and Poisson's ratio, $\nu = 0.18$.

This problem was also analyzed using one axisymmetric element. According to the test data the water content, w, varied with temperature as follows: 20°C, $w = 70$ kg/m^3; 130°C, $w = 15$ kg/m^3; 200°C, 300°C and 400°C, $w = 0$ kg/m^3. Because the water content is temperature dependent, the moisture effect on creep, f_w, must be taken into account. Since no shrinkage was observed during the tests, the water content, w, was assumed constant at each temperature level. The values of w_1 and w_0 (dried) were set as follows: $w_1 = w$ (at 20°C) = 70 kg/m^3 and $w_0 = w$ (at 200°C through 400°C) = 0 kg/m^3. Also, since the water contents are assumed constant, the effect of variable moisture content, $g(\hat{w})$, on creep is not needed. The double power law in Eq. (2) was calibrated for the creep data at reference temperature, $T_0 = 20$°C and initial water content, $w_1 = 70$ kg/m^3. This resulted in the following constants; $E_0 = 6.0 \times 10^6$ psi (41400 MPa), $\phi_1 = 5.788$, $t' = 150$ days, $m = 0.33$, $\alpha = 0.05$ and $n = 0.1215$.

With these material properties, the creep for higher temperatures and their corresponding moisture contents may be analyzed. The moisture effect on creep was varied by using different values of k_w = 0, 0.5, 0.8 and 0.9; ($f_w = 1.0 - k_w[(w_1 - w)/(w_1 - w_0)]$). In order to compare the different effects of moisture on creep, the creep strain at 400°C was set equal to the experimental creep strain for each value of k_w, by varying the value of creep activation energy, U_a/R, in ϕ_T for the temperature effect on creep. All calculation of equivalent hydration time were based on an activation energy of hydration, U_h/R = 2700°K. The results of the numerical study are shown in Fig. 2, the best fit was for k_w = 0.8 and U_a/R = 4910°K. If the moisture effect is neglected (i.e., k_w = 0), it is seen that the data cannot be matched as well.

Anderberg and Thelandersson also performed high temperature creep tests on concrete subjected to varying temperature and moisture conditions. The same type of concrete specimen described in the previous example was used. First, the specimens were initially loaded under different uniaxial compression of σ/f'_c = 0%, 22.5%, 35%, 45%, and 67.5% where f'_c = 43 MPa. After the compressive load was applied, the load was sustained while the temperature was raised from room temperature (20°C) to about 450°C at a rate of about 5°C per minute. Heating was applied to the outside of the cylinder and the deformation of the specimen was measured by passing a quartz rod through a 1.0 cm diameter hole in the specimen, as shown in Fig. 3a. Since the temperature is varying over the cross-section during heating, the temperature of the specimen was defined at a distance of 0.7 of the outer radius (= 2.6 cm) from the center. The results of the test are shown in Fig. 4 as the total strain, ε, as defined in Eq. (1), versus the temperature of the specimen under different sustained stress levels.

Based on these experimental results, further calibration of the constitutive relation may be performed because these tests had considerable moisture loss and thermal expansion during the deformation measurement. So the hygral and thermal strains, Eqs. (3), as well as the transient moisture effect on creep, $g(\hat{w})$ should be included in the analysis.

The thermal dilatation and shrinkage coefficient may be estimated by correlating the test data for the case of no axial load (σ/f'_c = 0%), shown in Fig. 4, because no creep is involved. Temperature and moisture calculations are accomplished by the TEMPOR2 code which has been developed for concrete axisymmetric elements. The finite element mesh for the temperature and moisture calculations are shown in Fig. 3b. Results of the temperature and moisture calculations along with the experimental results are indicated in Fig. 5 with a fairly good correlation. Structural calculations were done on the same finite element mesh to determine the constants α_T and k_s. The value of the shrinkage coefficient was assumed to be, $k_s = 1.0 \times 10^{-5}$ m^3/kg. By using the temperature and moisture content values in the structural calculations the best correlation was obtained for a thermal expansion of $\alpha_T = 1.3 \times 10^{-5}$/°C (Fig. 4a, σ/f'_c = 0%).

The creep parameters were evaluated using previous calibrations; U_a/R = 4910°K and k_w = 0.8 along with the transient moisture effect on creep. The results are shown in Fig. 4a for all the load levels including the zero axial load. Examining the experimental data indicates that the thermal and moisture dilatation is strongly reduced under stress and for a stress equal to about 40% of f'_c the net expansion is fully compensated by the stress-induced deformation. For illustration purposes the value of β was assumed the same for thermal and hygral strains in Eq. (3). The same analytical problem for Fig. 4a (β = 0) was now evaluated with different values of β until a proper correlation was found. Using β = 2.25 gave reasonable results, and is shown in Fig. 4b. By using the stress dependent constant the calculated values are now in better agreement with experimental results.

3. Conclusion

A viscoelastic creep formulation for high temperature effects has been incorporated into the implicit coupled thermal and stress analysis STRAW code. Also, the TEMPOR2 code (which provides the moisture and thermal effects in concrete) has been coupled with the structural calculations to provide the needed information for the constitutive model. This creep model does take into account the effects of constant and transient temperature, constant and transient moisture, and stress dependent thermal and shrinkage into the structural response of concrete subjected to the aforementioned temperature range.

The creep model was correlated with existing experimental data on high temperature response of concrete. Reasonable results were obtained for viscoelastic creep at stabilized temperature and moisture conditions. The stress dependent thermal and moisture effect was needed, however, to explain the overall response of concrete subjected to transient thermal and moisture conditions.

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References

[1] BAZANT, Z. P., ABRAMS, M. S., CHERN, J. C., GILLEN, M. P., "Normal and Refractory Concretes for LMFBR Applications," Vol. 1: Review of Literature on High-temperature Behavior of Portland Cement and Refractory Concretes, EPRI Report NP-2437 (June, 1982).

[2] BAZANT, Z. P., CHERN, J. C., THONGUTHAI, W., "Finite Element Program for Moisture Content and Heat Transfer in Heated Concrete," Nuclear Engineering and Design, 68, pp. 61-70 (1981).

[3] KENNEDY, J. M., BELYTSCHKO, T. B., SCHOEBERLE, D. F., "STRAW - A Nonlinear Fluid-Structural and Thermo-Mechanical Finite Element Program," ANL-85-4 (February, 1985).

[4] BAZANT, Z. P., "Mathematical Model for Creep and Thermal Shrinkage of Concrete at High Temperature," Nuclear Engineering and Design, 76, pp. 183-191 (1983).

[5] BAZANT, Z. P., CHERN, J. C., "Concrete Creep at Variable Humidity: Constitutive Law and Mechanism," Materials and Structures (RILEM, Paris), Vol. 18 (January-February, 1985).

[6] ANDERBERG, Y., THELANDERSSON, S., "Stress and Deformation Characteristics of Concrete at High Temperatures," Bulletin 54, Land Institute of Technology, Sweden (1976).

[7] BAZANT, Z. P., "Thermodynamics of Interacting Continua with Surfaces and Creep Analysis of Concrete Structures," Nuclear Engineering and Design, Vol. 20, pp. 477-505 (1972).

[8] BAZANT, Z. P., "Mathematical Models for Creep and Shrinkage of Concrete," Chapter 7 in: "Creep and Shrinkage in Concrete Structures," edited by Z. P. Bazant and F. H. Wittmann (John Wiley & Sons, Ltd., NY) pp. 163-256 (1982).

[9] MARECHAL, J. C., "Creep of Concrete as a Function of Temperature," Concrete for Nuclear Reactors, ACISP-34, Vol. 1, pp. 547-564, Detroit (1972).

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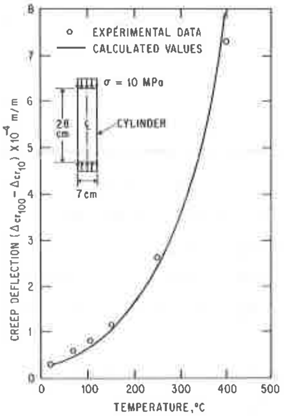

Fig. 1. Experimental [9] and Calculated Creep Values

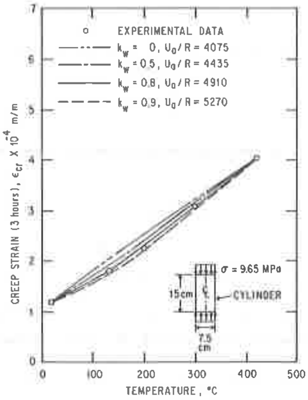

Fig. 2. Experimental [6] and Calculated Creep Values

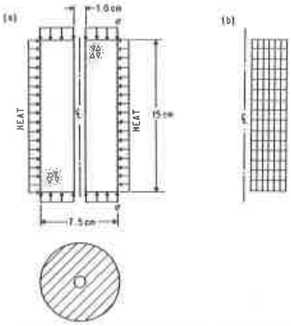

Fig. 3. Experimental [6] Concrete Cylinder and Analytical Model

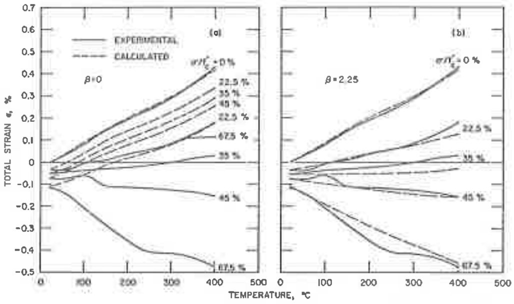

Fig. 4. Experimental [6] Simulation of Strain a) Without Stress Dependence, b) With Stress Dependence

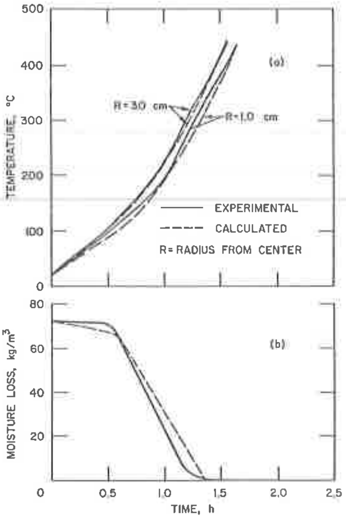

Fig. 5. Experimental [6] and Calculated Temperature and Moisture Response