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MASTER

Concrete Creep at Transient Temperature: Constitutive Law and Mechanism

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Abstract

A constitutive law which describes the transient thermal creep of concrete is presented. Moisture and temperature are two major parameters in this constitutive law. Aside from load, creep, cracking, and thermal (shrinkage) strains, stress-induced hygrothermal strains are also included in the analysis. The theory agrees with most types of test data which include basic creep, thermal expansion, shrinkage, swelling, creep at cyclic heating or drying, and creep at heating under compression or bending. Examples are given to demonstrate agreement between the theory and the experimental data.

1. Introduction

It was observed long ago [1] that loaded concrete shows a considerable increase in shrinkage when it is exposed to changing humidity. This effect, called the Pickett effect, was recently explained by a newly developed theory [6]. Meanwhile, the substantial increase of creep rates of the loaded concrete with changing temperature, known as transient creep [5] or transitional thermal creep [3], has not been explained.

In conventional design, engineers use creep data derived from steady-state (isothermal) creep tests. In these tests the concrete specimens are first heated to equilibrium and then the loads are applied. Since steady-state creep is considerably smaller than the transient creep [Fig. 1], it would be unsafe to neglect the excess deformation caused by transient heating. This is especially critical in cases where the temperatures can be high, as in the prestressed concrete reactor vessels. In this paper, we intend to describe the simulation of the transient thermal effect on concrete structures by extending the aforementioned new theory [6].

2. Constitutive Law and Numerical Algorithm

In the structural response of concrete structures exposed to high temperatures, various sources of deformation contribute to the total deformation of concrete. These are: (1) instantaneous elastic strain caused by the applied stress, (2) creep strain (significantly enhanced by temperature), (3) thermal expansion strain (composed of stress-induced and stress-independent components both affected by the thermal effects), (4) drying shrinkage strain (composed of stress-independent and stress-induced components accompanied by loss of evaporable water and swelling due to oversaturation of moisture), (5) cracking strains (associated with changes in the modulus of elasticity that occur during heating, drying, or mechanical loading), (6) volumetric strain due to pore pressure (caused by vaporization of moisture due to heating).

A newly developed constitutive relation [7] that includes all these phenomena has been recently implemented in the implicit finite element TEMP-STRESS program [8,9]. This constitutive relation is based on the rheological model which is graphically depicted in Fig. 2. It is composed of a series coupling of a cracking unit (deformation components, items 1 and 5), a Maxwell chain unit (items 1 and 2), and a unit reflecting shrinkage, dilatation and volume changes (items 3, 4 and 6). An efficient numerical algorithm, called the exponential algorithm [7], which had been introduced for viscoelastic material, was extended to cover the aforementioned items. This algorithm is unconditionally stable and accurate even for very large time steps. It also guarantees that the stress is always reduced to zero as the normal tensile strain becomes very large.

2.1 Viscoelastic Creep and Aging

The creep of concrete within the service stress range and temperatures up to about 350°C [10] can be approximated as being linearly viscoelastic with a strong aging effect. The aging viscoelastic behavior of concrete can be successfully represented by a rate-type formulation based on the Maxwell chain model. Furthermore, a computer subroutine MATPAR can be used to determine the age-dependent spring moduli E_μ and dash-pot viscosities η_μ stemming from the given basic creep test data. At reference temperature, the viscosity for Maxwell chain unit μ is given as $\eta_\mu(t) = \tau_\mu E_\mu(t)$, where τ_μ is the relaxation time.

2.2 Temperature and Moisture Effects

Both temperature and moisture influence the creep rate and hydration rate of concrete. This effect on creep rate is modeled by modifying the magnitude of the relaxation times for the Maxwell chain units. Equivalent hydration time, which is a function of temperature and moisture, is used to represent these effects on the hydration of concrete. The high temperature also causes a reduction in Young's modulus for concrete.

2.3 Moisture, Temperature Distribution and Pore Pressure

Concrete contains fine pores filled with water. Heating of concrete produces pore pressure which causes migration of moisture through concrete. At the same time, the movement of moisture through concrete may contribute to the heat transfer and hence change in temperature. A coupled heat and moisture transfer computer subroutine for concrete, TEMPOR2 [11], is used to predict the nonlinear moisture, temperature distribution and pore pressure.

2.4 Stress-Strain Relation

Microcracks which develop due to variation of temperature and moisture content in concrete are modeled as a gradual and irreversible strain-softening instead of a brittle cracking with a sudden stress reduction to zero after the attainment of the tensile strength limit. The model is based on fracture test data and some recently obtained tensile strain-controlled experimental data. The relation between stress, σ, and cracking strain, ξ, in the analysis is defined by a secant modulus $C(\xi,T)$, which is a function of the cracking strain and temperature. For a uniaxial stress-strain relation, the secant modulus is assumed as $C(\xi,T) = E_s \exp(-c\xi^s)$, where c, s, E_s are empirical constants relating to temperature T. Microcracking, which causes strain-softening, is permitted to take place only within three principal orthogonal planes. This permits strain-softening by independent algebraic relations for each of the three orthogonal directions, including independent unloading and reloading behavior. The changes of experimental stress-strain curves at high temperatures are described by changes of elastic modulus, creep and fracturing strain of concrete due to temperature contribution from creep becomes significant when temperatures exceed 400°C.

2.5 Stress-induced Thermal Expansion and Shrinkage

From experimental data studies [12,6] and their mathematical analysis [6], stress-induced thermal expansion and shrinkage were found to be of great importance in the analysis of concrete structures subjected to changing temperature and humidity. In ref. 6, these stress-induced strains are derived according to a thermodynamic theory based on a certain hypothesis concerning microscopic mechanism of creep -- the creep viscosities depend on the magnitude of the flux of microdiffusion of water between the macropores (capillary pores) and the micropores in the cement gel. By assuming this microdiffusion to be infinitely fast, the effect is reduced to a dependence of creep viscosities on the time rate of pore humidity and temperature. This is further shown to be equivalent to stress-induced thermal dilatation and shrinkage.

A recent study [13] has furthermore improved the previous assumption making the creep viscosity, η, dependent on the absolute value of microdiffusion flux, j, between macropores and micropores, i.e. $1/\eta$ = function of $|j|$. From ref. 13, we obtain

$$j = a_1 \dot{H} \qquad \text{with } \dot{H} = \dot{h} + a_T \dot{T} \tag{1}$$

where $\dot{H}$ is the effective humidity rate, a_1 is a constant and a_T is the hygrothermic coefficient (positive); h, T represent the humidity and temperature, respectively. Then, the rates of shrinkage and thermal expansion are found to be

$$\dot{\varepsilon}_{sh} = \kappa_0 (1+r\sigma \text{ sign } \dot{H})\dot{h}, \qquad \dot{\varepsilon}_T = \alpha_0 (1+\rho\sigma \text{ sign } \dot{H})\dot{T} \tag{2}$$

in which κ_0 is the shrinkage coefficient and α_0 is the thermal expansion coefficient; r and ρ are material constants for stress-induced shrinkage and stress-induced thermal expansion, and σ is the stress. The concepts of stress-induced shrinkage and stress-induced thermal expansion are the same as those introduced recently for wood [14]. It may also be shown that they follow as special cases from a general thermodynamic theory for concrete as a two-phase absorbent material [15,6]. Equation (2) permits extending the analysis to concrete structures subjected to heating, cooling, drying, wetting or cyclic environmentally changing conditions.

3. Identification of Material Constants

After setting up the constitutive relation for concrete, a set of experiments are needed to identify the necessary material parameters: (1) basic creep tests for E_μ, η_μ, τ_μ and aging; (2) steady-state creep tests with very slow heating rate for the activation energy coefficient; (3) creep tests at various degrees of moisture to yield the moisture effect coefficient; (4) shrinkage test and thermal test to yield the shrinkage, thermal expansion coefficient from inference; (5) tensile and compressive strain-controlled load-displacement tests at various temperatures to obtain the softening parameters; (6) transient moisture creep tests at room temperature for the stress-induced shrinkage constant; (7) transient thermal creep tests for the stress-induced thermal constant. Constant a_T of Eq. (1) can be determined by thermodynamic theory or empirical calibration.

4. Analysis of Test Data

Tests of small specimens provide the basic information to extend analysis to full scale structures. However, one has to be careful in studying the small specimen test data. Many factors, like the initial moisture state of the specimen (curing process) or the formation of cracking due to shrinkage, have a great effect on the behavior of small test specimens. The previous constitutive law described here has been introduced into the thermo-mechanical finite element code TEMP-STRESS [8,9] to analyze the test data. The following typical test data will be discussed:

4.1 Drying at Room Temperature ($\dot{H}<0$, $\dot{h}<0$, $\dot{T}=0$)

The Pickett effect can be seen from this type of test; the prediction results are shown in ref. 6.

4.2 Mild Heating or Cooling in Water ($\dot{H}>0$, $\dot{h}=0$, $\dot{T}>0$ for heating)

A cement mortar beam with dimension 0.8 x 2 x 10 in. was immersed in water and subjected to bending and different rates of heating [2]. The apparent increase of central deflection of the mortar beam due to the transient thermal effect at an early period of test duration is apparent in Fig. 3. The beam which was subjected to a higher heating rate yields more deflection. The test results are predicted well by the theory. Neglecting the moisture effect, this case can be explained purely by the transient thermal effect.

4.3 Mild Heating at 50% and 100% Relative Humidity (R.H.)

Results of the creep study [4] conducted on hollow cylindrical microconcrete specimens with inner diameter 5 in., and outer diameter 6 in. are used for analysis. The temperature in the test specimens reach equilibrium very soon due to the thin wall thickness, and the transient temperature effect occurs only at the time temperature is increased or decreased. However, the drying process continues at the higher temperature, in contrast to the ambient temperature. Therefore, the transient thermal creep shown in Fig. 4 is primarily the result of Pickett effect. For tests done at 50% R.H., the Pickett effect is obvious during the first 60 days and becomes unimportant after that due to low moisture loss (Fig. 5). In Fig. 4, the calculation results obtained in steady-state creep tests are indicated by the line a, the difference between this line and experimental test data is pronounced.

4.4 Fast Heating in the Air (Temperature 300°C, $\dot{T} > 0$, $\dot{H} > 0$)

Cylindircal specimens of 3.15 in. diameter and 12 in. length were subjected to fast heating rate [5]. The fast heating also induced rapid moiture transfer in the specimen; it caused fast drying at the surface of specimen and saturation at the center. In this case, the effect of $\dot{T}$ dominates the magnitude of $\dot{H}$. From Eq. 1, we see that the shrinkage strain increment is smaller for specimen subjected to compressive load, this is opposite to the Pickett effect. Therefore, the transient thermal effect at fast heating conditions is controlled by the temperature change. Figure 6 shows the comparison betwen test data and theory obtained at steady-state and transient state condition.

5. Conclusions

1. Transient thermal creep can be explained by the presented theory. This is ascertained by different types of test data. The principal features of the theory are: (i) stress-induced thermal expansion and shrinkage; (ii) tensile strain softening

due to progressive cracking; (iii) irreversible unloading after tensile strain softening; (iv) increase of material stiffness due to aging.

2. Both temperature and moisture are important in modeling transient thermal creep in concrete structures. As temperature reaches equilibrium in the test specimen, the excess creep which continues to develop is purely due to the Pickett effect.

Acknowledgments

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References

1. PICKETT, G., "The Effect of Change in Moisture Content on the Creep of Concrete under a Sustained Load," ACI Journal, Vol. 38, pp. 333-355 (1942).

2. HANSEN, T.C. and ERIKSSON, L., "Temperature Change Effect on Behavior of Cement Paste, Mortar, and Concrete Under Load," ACI Journal, Vol. 1, pp. 489-504 (1966).

3. ILLSTON, J. M. and SANDERS, P. D., "The Effect of Temperature Change Upon the Creep of Mortar under Torsional Loading," Mag. of Con. Res., Vol. 25, No. 84, pp. 136-144 (1973).

4. FAHMI, H. M. et. al., "Effect of Sustained and Cyclic Elevated Temperature on Creep of Concrete," Cement and Con. Res., Vol. 2, pp. 591-606 (1972).

5. SCHNEIDER, U., "Behavior of Concrete under Thermal Steady State and Non-Steady State Condition," Fire and Materials, Vol. 1, pp. 103-11 (1976).

6. BAŽANT, Z. P. and CHERN, J. C., "Concrete Creep at Variable Humidity: Constitutive Law and Mechanism," Material and Structures (RILEM, Paris), Vol. 18, Jan-Feb (1985).

7. BAŽANT, Z. P. and CHERN, J. C., "Strain-Softening with Creep and Exponential Algorithm," J. of Eng. Mechanics, ASCE, Vol. III (1985).

8. MARCHERTAS, A. H., "Thermo-Mechanical Analysis of Concrete in LMFBR Program," Nucl. Eng. and Design, Vol. 82, No. 1, pp. 47-62 (1984).

9. KENNEDY, J. M., et al., "STRAW - A Nonlinear Fluid-Structural and Thermo-Mechanical Finite Element Program," Argonne National Laboratory, Report No. ANL-85-4 (Feb. 1985).

10. GROSS, H., "High-Temperature Creep of Concrete," Nucl. Eng. and Design, Vol. 32, pp. 129-147 (1975).

11. BAŽANT, Z. P. and THONGUTHAI, W., "Pore Pressure and Drying of Concrete at High Temperature," J. Eng. Mech. Div., ASCE, Vol. 104, pp. 1059-79, (1978).

12. ANDERBERG, Y. and THELANDERSON, S., "Stress and Deformation Characteristics of Concrete at High Temperatures, 2. Experimental Investigation and Material Behavior Model," Bulletin 54, Lund Institute of Technology, Lund, Sweden (1976).

13. BAŽANT, Z. P. and CHERN, J. C., "Constitutive Model for Transient Thermal Creep of Concrete," in preparation (1985).

14. BAŽANT, Z. P., "Constitutive Equation for Wood at Variable Humidity and Temperature," Report to U.S. Forest Products Laboratory in Madison, Wisconsin, Northwestern Univ., Evanston, IL (1982); also Wood Science and Technology, No. 2 (1985).

15. BAŽANT, Z. P., "Thermodynamic of Interacting Continua with Surfaces and Creep Analysis of Cement Structures," Nucl. Eng. and Design, Vol. 20, pp. 477-505 (1972).

Figure Captions

Fig. 1. Sketch of Transient Thermal Creep

Fig. 2. Rheological Model with Cracking

Fig. 3. Fits of Test Data by Hansen

Fig. 4. Fits of Test Data by Fhmai et al.

Fig. 5. Fits of Test Data by Fhmai et al.

Fig. 6. Fits of Test Data by Schneider

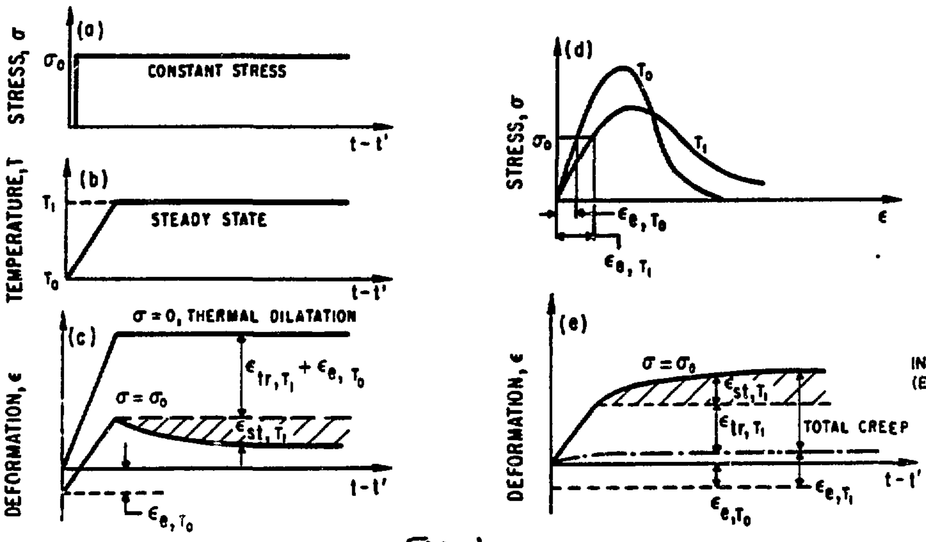


Fig. 1

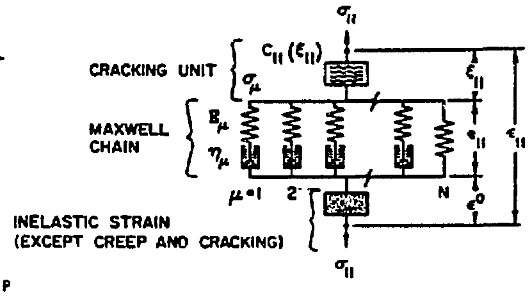


Fig. 2

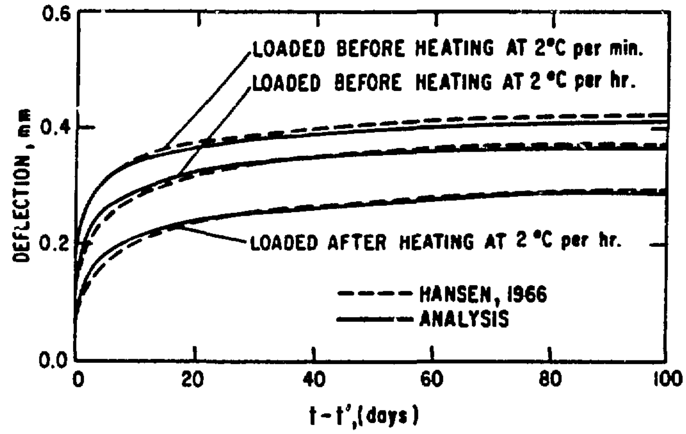


Fig 3

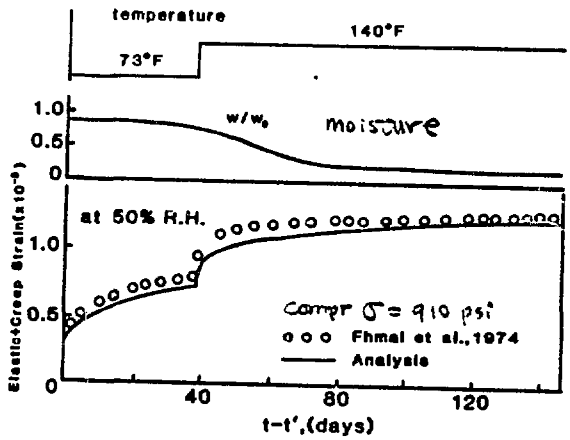


Fig. 4

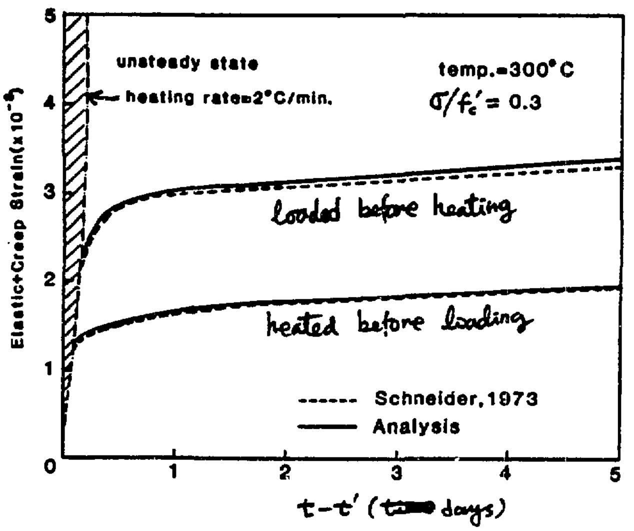


Fig. 6

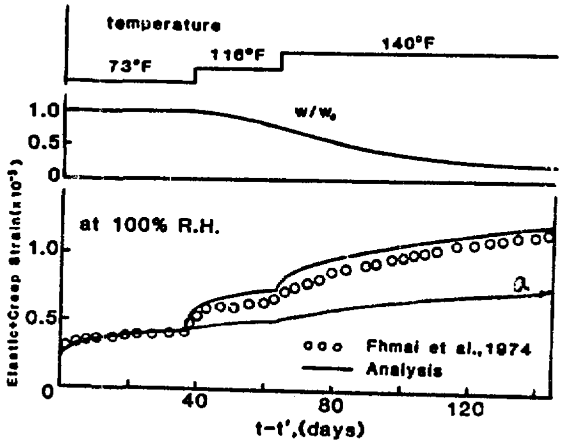
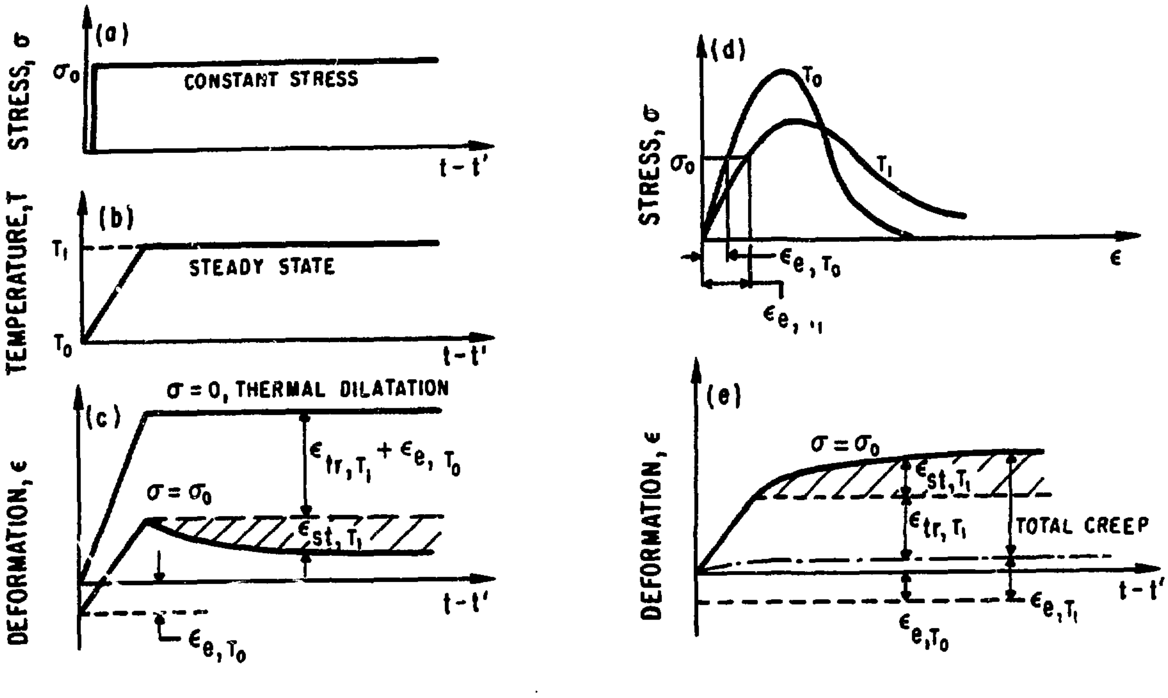
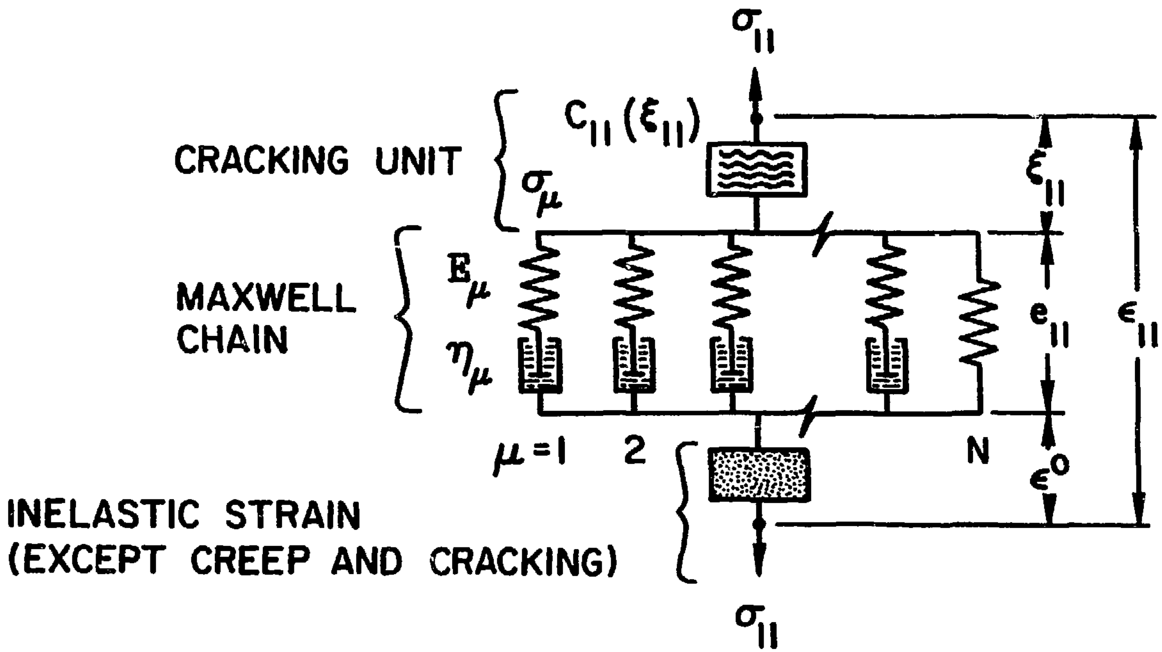
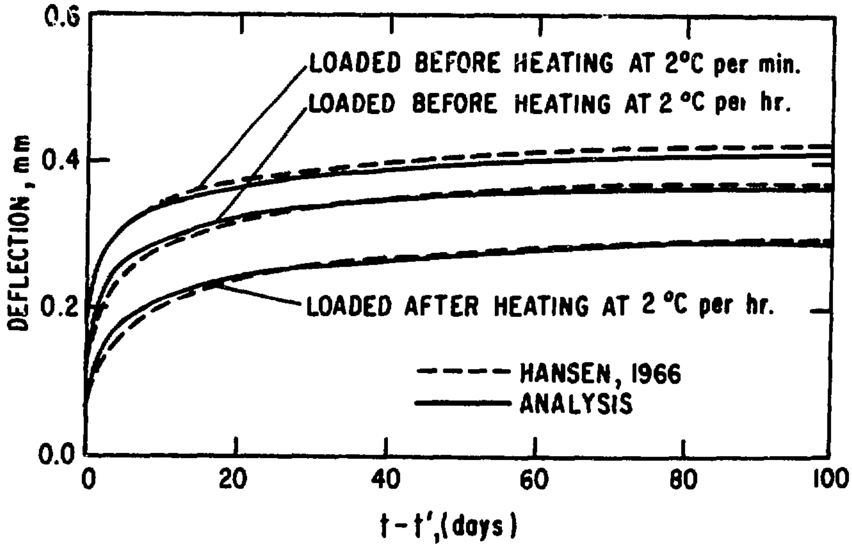


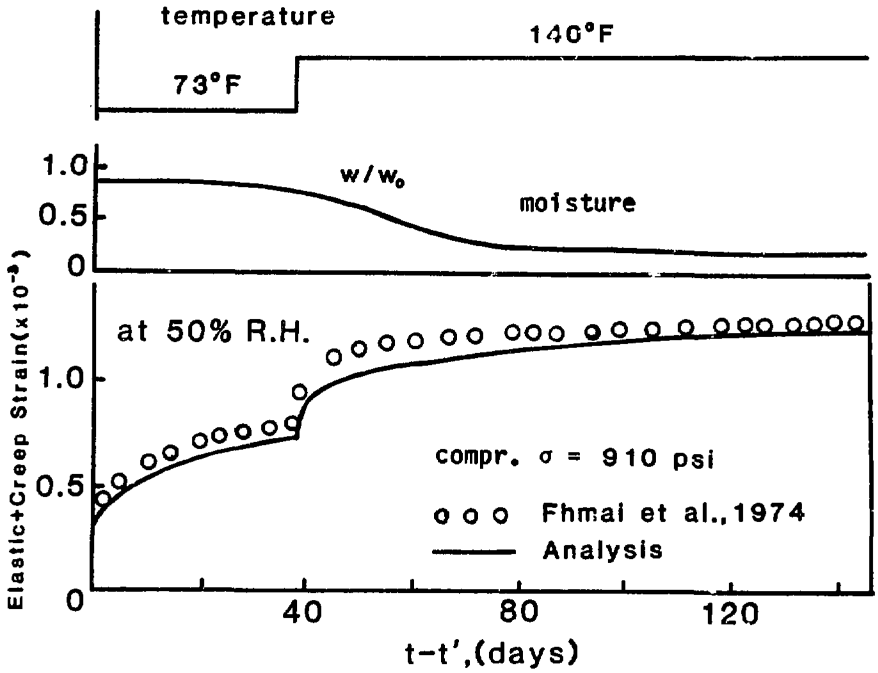
Fig. 5

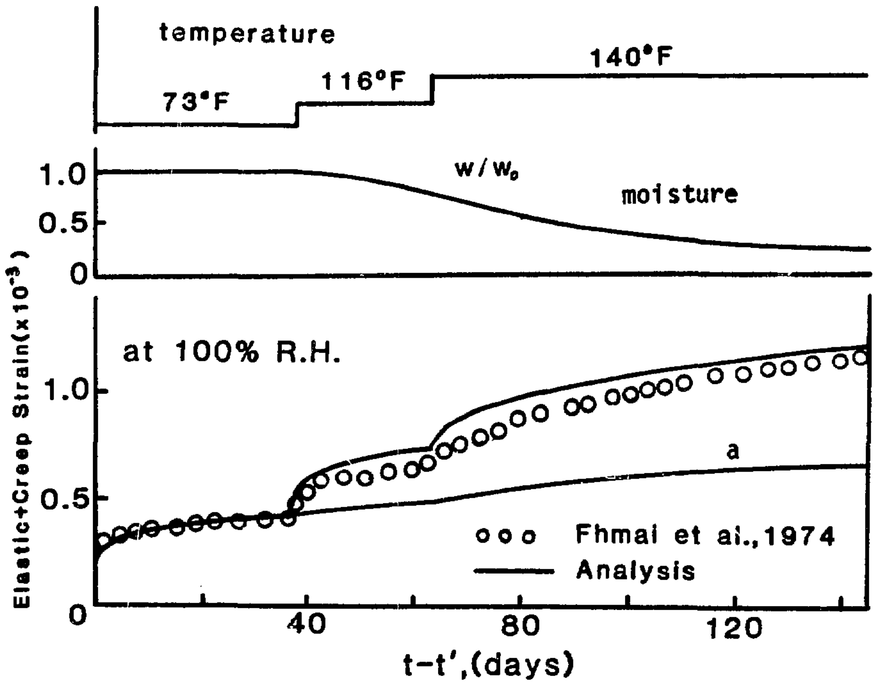

STRESS, σ
(a)
σ0
CONSTANT STRESS
t - t'
TEMPERATURE, T
(b)
T1
T0
STEADY STATE
t - t'
DEFORMATION, ε
(c)
σ = 0, THERMAL DILATATION
σ = σ0
ε tr, T1 + ε e, T0
ε st, T1
ε e, T0
t - t'
STRESS, σ
(d)
σ0
T0
T1
ε e, T0
ε
DEFORMATION, ε
(e)
σ = σ0
ε st, T1
ε tr, T1
TOTAL CREEP
ε e, T1
ε e, T0
t - t'

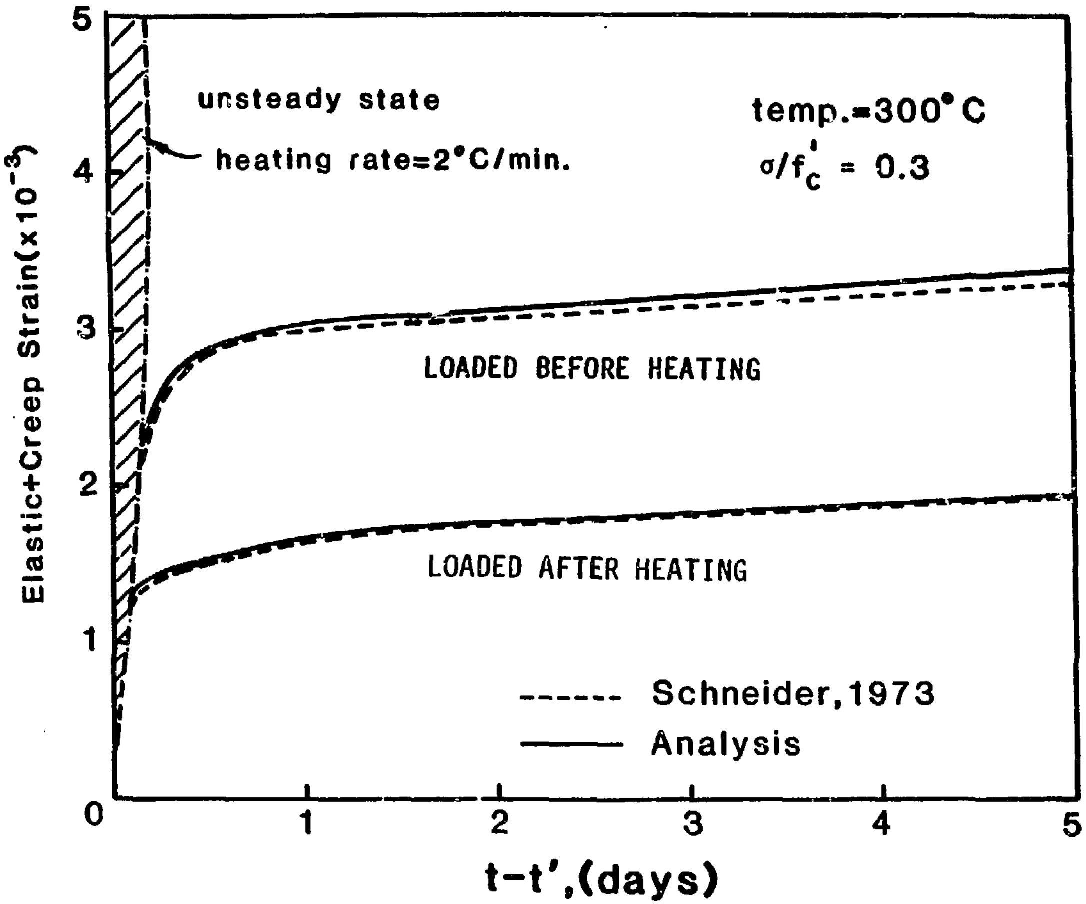

σ_{11}
$C_{11}(\xi_{11})$
CRACKING UNIT
σ_μ
ξ_{11}
MAXWELL
CHAIN
E_μ
η_μ
e_{11}
ϵ_{11}
$\mu=1$
2
N
ϵ^0
INELASTIC STRAIN
(EXCEPT CREEP AND CRACKING)
σ_{11}



0.6
0.4
0.2
0.0
DEFLECTION, mm
LOADED BEFORE HEATING AT 2°C per min.
LOADED BEFORE HEATING AT 2 °C per hr.
LOADED AFTER HEATING AT 2 °C per hr.
HANSEN, 1966
ANALYSIS
0
20
40
60
80
100
t - t', (days)


temperature
140°F
73°F
1.0
0.5
0
w/w₀
moisture
Elastic+Creep Strain(x10⁻³)
at 50% R.H.
1.0
0.5
0
compr. σ = 910 psi
o o o Fhmai et al.,1974
Analysis
40
80
120
t-t',(days)


temperature
140°F
116°F
73°F
1.0
0.5
0
w/w₀
moisture
Elastic+Creep Strain(x10⁻³)
at 100% R.H.
1.0
0.5
0
a
o o o Fhmai et ai.,1974
Analysis
40
80
120
t-t',(days)



unsteady state
heating rate=2°C/min.
temp.=300°C
σ/f'c = 0.3
LOADED BEFORE HEATING
LOADED AFTER HEATING
Schneider,1973
Analysis
Elastic+Creep Strain(x10^-3)
t-t',(days)
0
1
2
3
4
5