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Autor: Mukaddam, Muhammad

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Behavior of Concrete under Variable Temperature and Loading

MUHAMMAD MUKADDAM
Assistant Professor
American University of Beirut
Lebanon

For designing concrete structures subjected to thermal gradients, the structural engineer requires the complex constitutive time and temperature dependent relations of concrete. Below, a mathematical model is developed which generates the specific compliance surface of concrete for temperatures ranging between 68°F - 200°F, age at loading varying between 28-400 days, and observation time up to 1000 days after loading. The mathematical model is developed for sealed specimen with stress/strength ratio of 35-45% or less.

Terminology:

specific creep = time dependent deformation/unit stress
specific compliance = instantaneous + time dependent deformation/unit stress
thermal strain = $\alpha \Delta T$, where

α = coefficient of thermal expansion
ΔT = change in temperature

T.S. material = thermorheologically simple material.

* * *

In order to develop the mathematical model the effects of the temperature to which the concrete is subjected to are first studied. Then the effects of age of concrete at loading are discussed separately. Finally the effects of varying the two above parameters simultaneously are determined.

Temperature Effects:

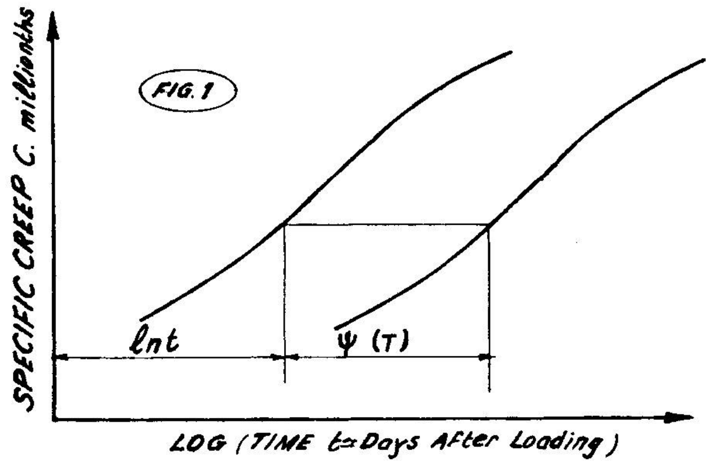
It is demonstrated that concrete under some conditions behaves as a thermorheologically simple material. In order to decide whether a material is T.S. or not one has to check whether all experimental curves of creep at different temperatures fit together by shifting them along the axis of logorithmic time.

Mathematically, the principle of shift function is simple. Let T_o be a known fixed reference temperature, and T a constant temperature $T > T_o$.

Then as seen from Fig. 1,

$$C_T(\ell nt) = C_{T_o}(\ell nt + \psi(T))$$

or ln (t) for T curve corresponds to $(\ell n(t) + \psi(T))$ for the T_o curve. Thus t for T curve corresponds to $\mathrm{Exp}(\ell nt + \psi(T))$ for T_o curve, but $\mathrm{Exp}(\ell nt + \psi(T)) = t\,\mathrm{Exp}(\psi(T))$ call $\mathrm{Exp}(\psi(T)) = \phi(T) \equiv$ shift function for temperature T having T_o as reference temperature.



Hence knowing the specific creep curve at one temperature for T.S material one can determine the specific creep curves for that material at any other constant temperature T, by simply replacing the argument t in reference curve by t ϕ (T).

The number of reliable published experimental results on creep characteristics of concrete at high temperatures is limited. Using the available data it is demonstrated that concrete behaves as a T.S material for temperatures between 60 - 200 °F and age at loading of 10 days or more.

A.D. Ross (Ref 1) presented data for total strain (elastic + creep)/ksi for uniaxial cylinders loaded for 80 days at different temperatures ranging from 68°F to 284°F.

All specimens were sealed and loaded at an age of 10 days. Also included in the data is the instantaneous response on loading for different temperatures. Fig. (2) shows how good the fit is for different temperatures, ranging from 68°F - 176°F.

Another independent set of data is obtained from Ref.(2) by D. Hannant. In this case concrete was cured for 24 hours under wet sacks before demolding, followed by five months under water at 20°C (68°F) and one month in the sealed saturated condition. The temperature range that the concrete was subjected to, is 27°C - 77°C (80.6-170.6°F). Figure (3) shows that the shift principle leads to accurate results in this case.

Effect of Age at Loading:

It is known that specific creep is a function of age at loading. Recently, research has been done on the mathematical form of the function representing the variation in the specific creep with a change in the age at loading of concrete.

After close examination of the shapes of the specific creep curves at different ages of loading, and keeping in mind that the rate of chemical reaction in concrete is affected by temperature as well as by time, the following is proposed:

If $C_{(K_0)} = \sum_{i=1}^{n} C_i \, e^{-\lambda_i t}$

represents the specific creep at a certain reference age at loading K_0,

where C_i , λ_i are constant coefficients, and t is time in days after loading.

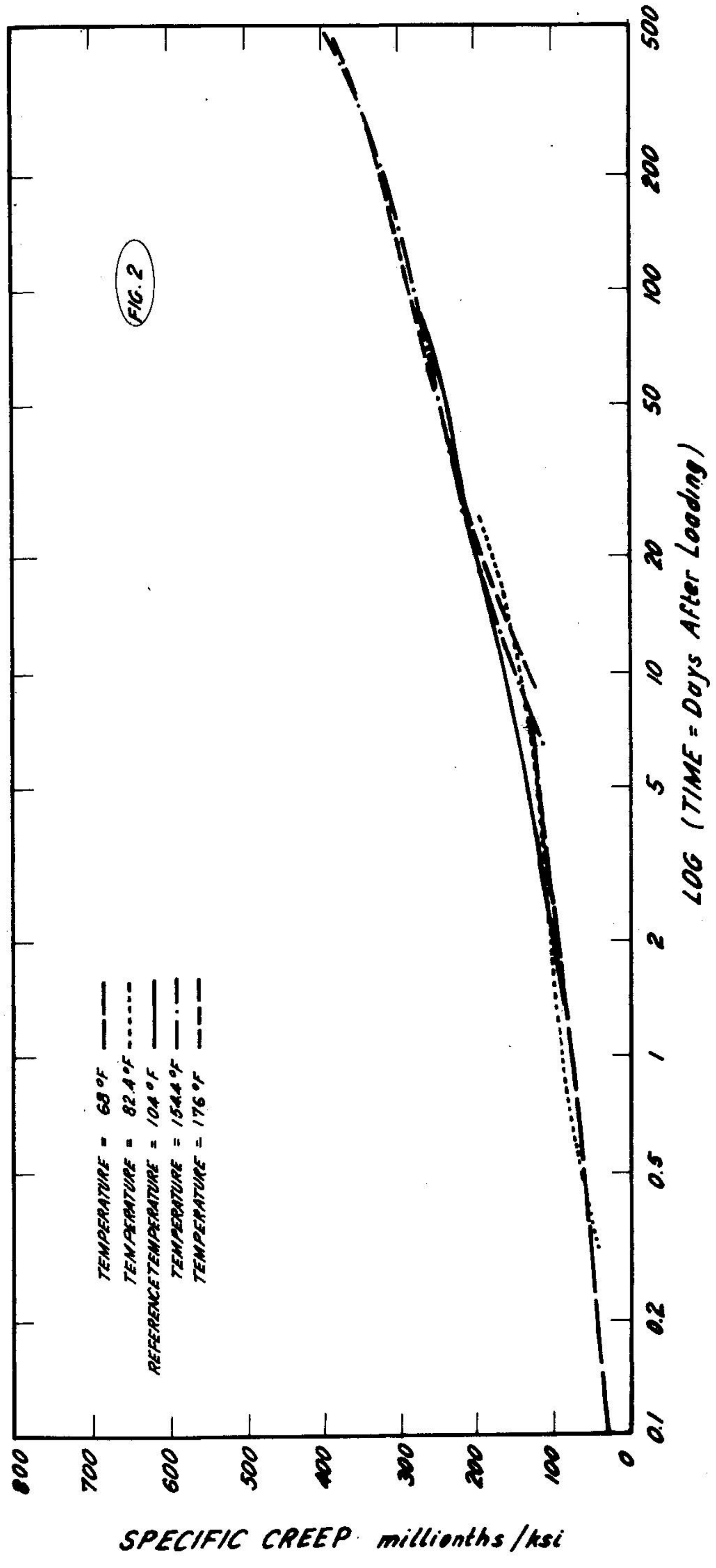


FIG. 2
TEMPERATURE = 68°F
TEMPERATURE = 82.4°F
REFERENCE TEMPERATURE = 104°F
TEMPERATURE = 154.4°F
TEMPERATURE = 176°F
0.1
0.2
0.5
1
2
5
10
20
50
100
200
500
LOG (TIME = Days After Loading)
0
100
200
300
400
500
600
700
800
SPECIFIC CREEP millionths/ksi

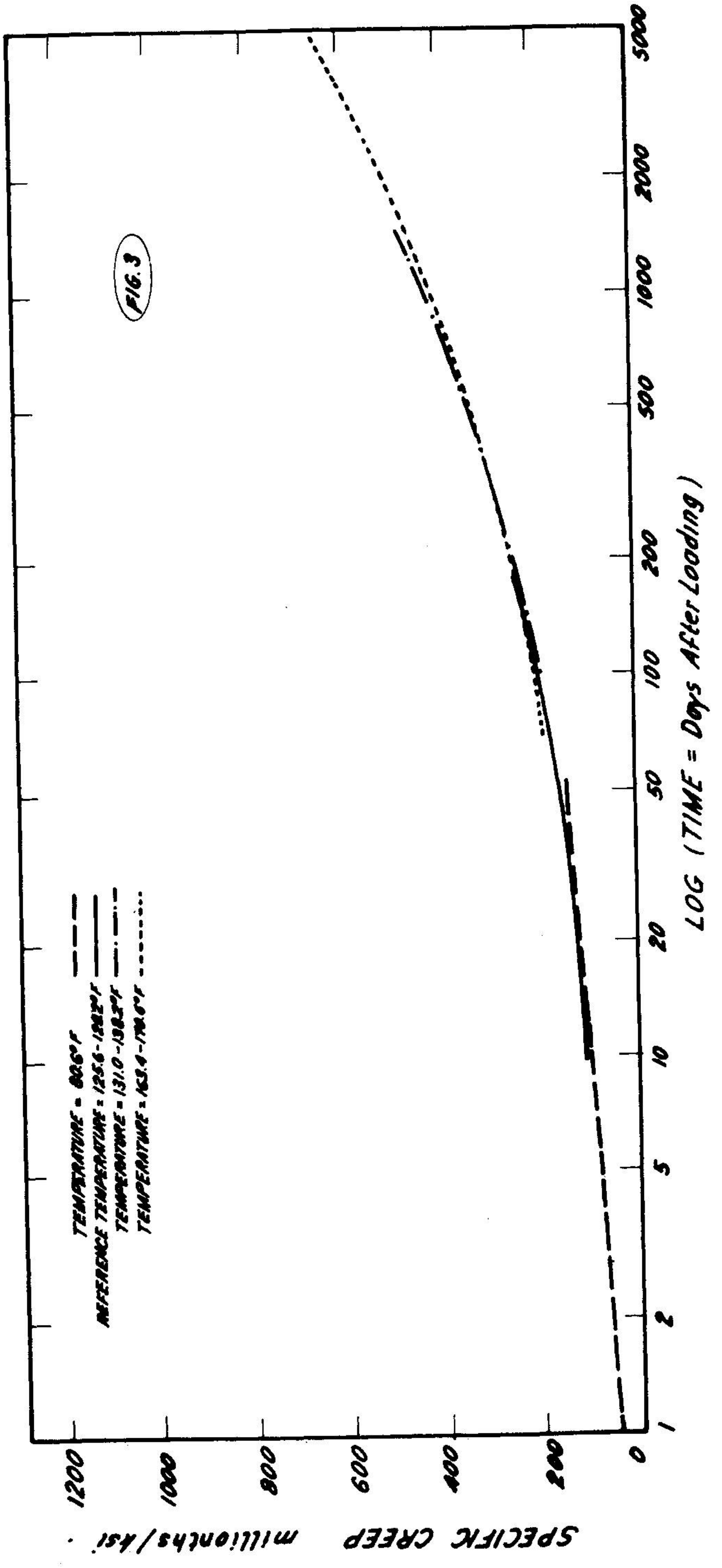


FIG. 3
TEMPERATURE
REFERENCE TEMPERATURE
TEMPERATURE
TEMPERATURE
SPECIFIC CREEP millionths/ksi
0
200
400
600
800
1000
1200
1
2
5
10
20
50
100
200
500
1000
2000
5000
LOG (TIME = Days After Loading)

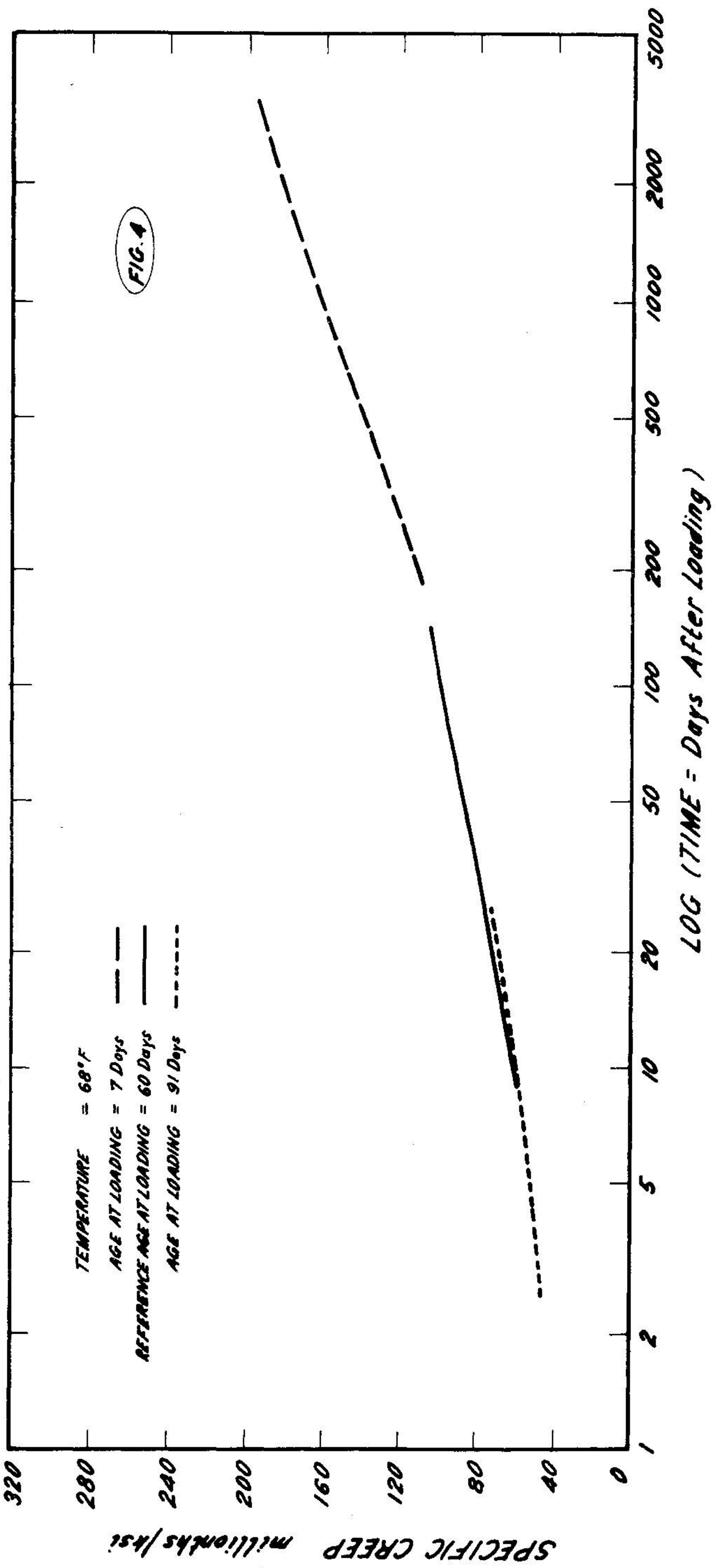


FIG. 4
TEMPERATURE = 68°F
AGE AT LOADING = 7 Days
REFERENCE AGE AT LOADING = 60 Days
AGE AT LOADING = 91 Days
1
2
5
10
20
50
100
200
500
1000
2000
5000
LOG (TIME - Days After Loading)
0
40
80
120
160
200
240
280
320
SPECIFIC CREEP millionths/psi

then $C_{(K)} = \sum_{i=1}^{n} C_i \, e^{-\lambda_i t \psi_1(K)}$

represents the specific creep of the concrete loaded at a different age K. This is similar to temperature shift function principle.

$\psi_1(K)$ is the shift function for ageing of the concrete.

To check the validity of this proposal, the same data used by Selna Ref. (3) and presented by A. Ross (4) is used. Figures (4,5) show how good the proposed model is. In addition to giving good results, this method is simple to apply, gives better interpolation valves than Selna's Model, and much better extrapolation valves for specific creep. This principle leads to a compatible formulation for the simultaneous consideration of temperature and age at loading on the creep characteristics of concrete.

Combined Effects of Temperature and Ageing on Creep Characteristics of Concrete:

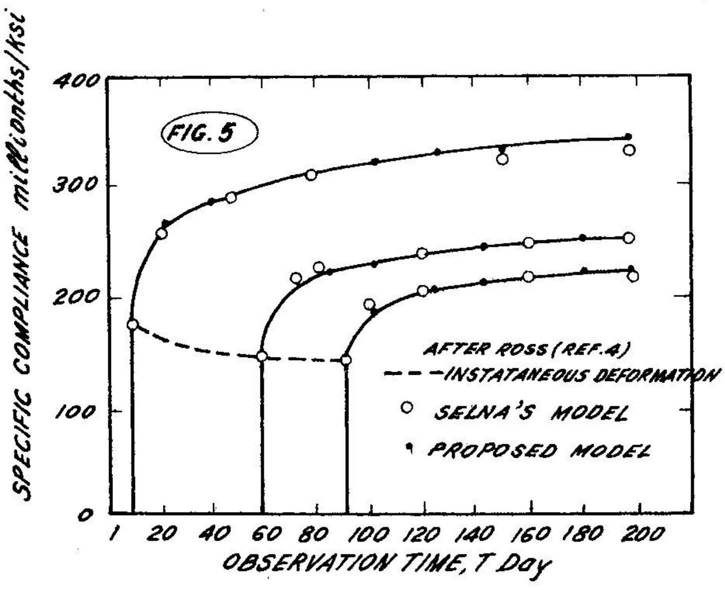
If temperature and age at loading of concrete were independent then the principle of shift function could be applied simply as:

If $C = \sum_{i=1}^{n} C_i \, e^{-\lambda_i t}$ represents the specific creep of concrete at reference temperature T_0 and reference age at loading K_0 , then

$C = \sum_{i=1}^{n} C_i \, e^{-\lambda_i t \phi(T) \psi_1(K)}$ gives the specific creep for same concrete loaded at an age of K and temperature T.

However, since it is known that age of concrete (maturity) is a function of temperature, the following form of shift function is proposed.

$TS(K, T) = \phi(T) \; \psi_1(K, T)$



Where TS (K,T) is the total amount the specific creep curve loaded at an age K and temperature T needs to be shifted to fit the reference creep curve.

$\phi(T)$ is the temperature shift function as discussed before.

It is proposed that

$$\psi(K,T) = \psi(\text{COAGE}(K,T))$$

where $\text{COAGE}(K,T) = K_o + (K-K_o)\, e^{-A(T-T_o)}$

where K_o, T_o are the reference age at loading and temperature respectively.

A - is a constant obtained in such a way that the curve $\psi(K,T)$ gives a continuous monotonic curve so that interpolation from such curve is possible.

General Procedure for Finding Shift Functions:

1- Calculate the specific creep for each case where $C(t,\tau)$ = specific compliance (t,τ). Instantaneous strain (τ), where t is observation time. τ is age at loading.

2- Plot all specific creep curves on semi-log papers.

3- Select the specific creep curve corresponding to reference age at loading K_o and reference temperature T_o as the reference curve.

4- By shifting the specific creep curves corresponding to age at loading K_o and different temperatures T_1, T_2, T_3 etc... determine the temperature shift function $\phi(T)$.

5- By shifting the rest of the specific creep curves corresponding to different temperatures and ages at loading so that they fit the reference specific creep curve, determine TS (K,T).

6- Determine $\psi(K,T) = TS(K,T) / \phi(T)$ for each specific creep curve.

7- By trial and error between steps 7 and 8, determine A such that $\psi_1(\text{COAGE}(K,T))$ will be a smooth monotonic curve. Then determine COAGE (K,T) for each case as $\text{COAGE}(K,T) = K_o + (K-K_o)\,\text{Exp}(A(T-T_o))$.

8- $\psi(\text{COAGE}(K,T))$ is determined and plotted.

Thus with the above procedure the specific creep for any temperature and any age at loading can be determined.

Verification of Above Procedure:

There is extremely limited data on the response of concrete loaded at different ages and different temperatures.

R. Browne Ref. (5) presented data for concrete loaded at ages of 28, 60, 180, 400 days and for each age some specimens were subjected to 68, 104, 149 and 200°F.

For this concrete, the specific creep curve corresponding to age at loading 28 days and temperature 68°F is chosen as reference. The equation which represents the reference curve is found.

$$C(28,68) = 919.01 - 46.27\, e^{-.2t} - 95.08\, e^{-.02t} - 156.32\, e^{-.002t} - 197.60\, e^{-.0002t} - 370.22\, e^{-.00002t} \quad (1.a)$$

where t is time in days after loading.

The shift function $\phi(T)$ is found in this case to be

$$\phi(T) = -3.55\left(\frac{T}{68}\right)^3 + 21.57\left(\frac{T}{68}\right)^2 - 33.83\left(\frac{T}{68}\right) + 16.79 \quad (1.b)$$

where T is temperature in ^oF.
$\phi(T)$ is temperature shift function.

Also it is found that in this case

$$\text{COAGE}(K,T) = K_o + \sum_{i=1}^{n} \Delta k(i)\, e^{-A(T(i)-T(o))}$$

$$\text{or COAGE}(K,T) = 28. + \sum_{i=1}^{n} \Delta k(i)\, e^{-0.6(T(i)-68)} \quad (1.c)$$

where $(K_o + \sum_{i=1}^{n} \Delta K(i))$ gives actual age of concrete in days if no corrections for temperature, or temperature history are applied.

$$\psi_1(\text{COAGE}(K,T) = .056 + .686\, e^{-.01(\text{COAGE}(K,T))}$$

$$\text{for COAGE} \geq 28.3 \text{ days} \quad (1.d)$$

The instantaneous deformation / ksi is found as a function of age at loading and temperature.

$$\text{Instantaneous def. } (\tau)/\text{ksi} = 210.\left\{-.086\left(\frac{T}{68}\right)^3 + .352\left(\frac{T}{68}\right)^2 - .019\left(\frac{T}{68}\right) + .753\right\} + \frac{1600}{\tau} \quad (1.e)$$

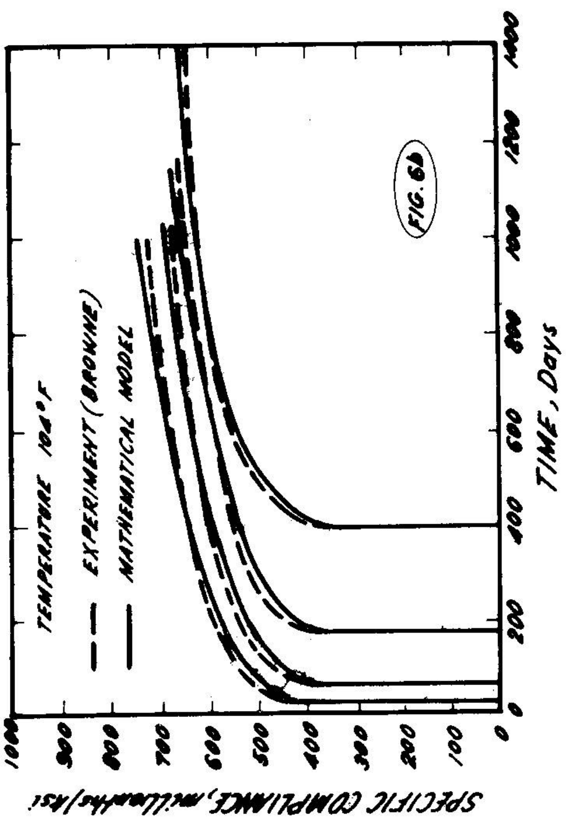
where τ is the times at loading in days
T is temperature in ^oF.

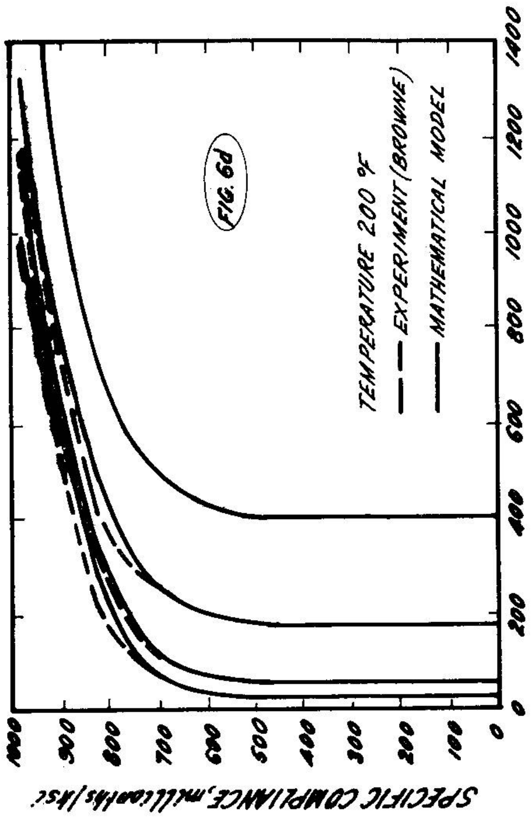
Using the above mathematical Model equations (1.a - 1.e) the total deformation/ ksi for all the cases are computed and plotted as shown in Figs. (6.a - 6.d).

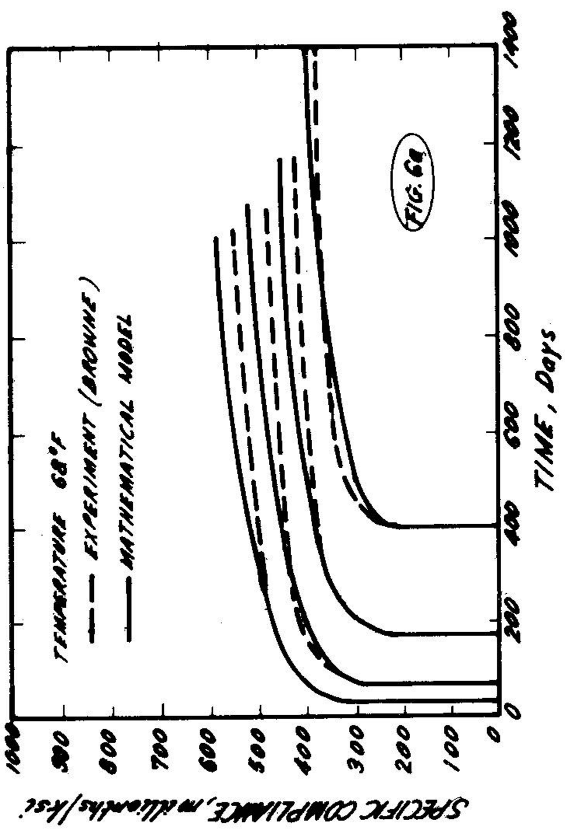
The results fit well with the experimental results if one considers the accuracy of results of experimental work Ref.(5).

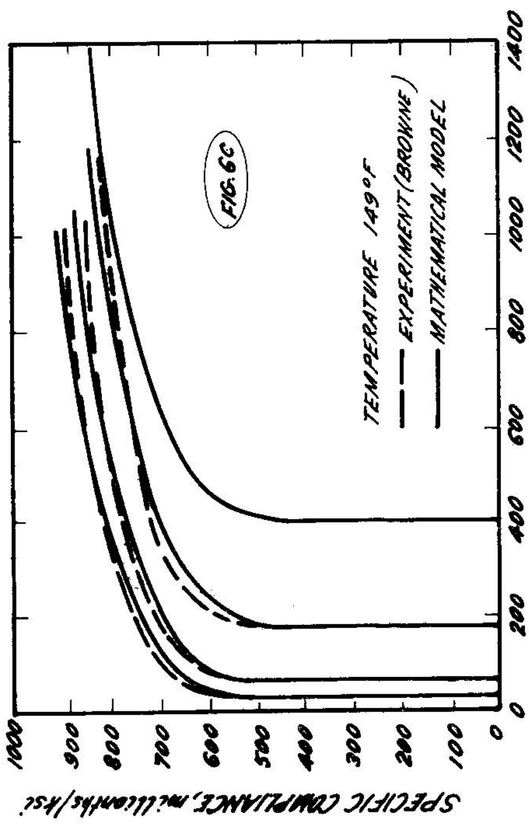
To illustrate the capability of the mathematical model two examples in which simple uniaxial concrete cylinders are subjected to different loads and temperatures are solved. Also, a study of the behavior of a concentrically prestressed concrete beam subjected to thermal gradients is done. Finally, in order to simulate the nuclear reactor pressure vessel, a thick-wall ring structure subjected to internal thermal gradients, internal pressure and external pressure (Prestressing) is analyzed.

Incremental approach using finite element method is used in the solution of these structural problems. It is only for the lack of space that the results of these examples shall not be included here.


TEMPERATURE 104°F
EXPERIMENT (BROWNE)
MATHEMATICAL MODEL
FIG. 6b
SPECIFIC COMPLIANCE, millionths/ksi
TIME, Days


TEMPERATURE 200 °F
EXPERIMENT (BROWNE)
MATHEMATICAL MODEL
FIG. 6d
SPECIFIC COMPLIANCE, millionths/ksi
TIME, Days


TEMPERATURE 68°F
EXPERIMENT (BROWNE)
MATHEMATICAL MODEL
FIG. 6a
SPECIFIC COMPLIANCE, millionths/ksi
TIME, Days


TEMPERATURE 149°F
EXPERIMENT (BROWNE)
MATHEMATICAL MODEL
FIG. 6c
SPECIFIC COMPLIANCE, millionths/ksi
TIME, Days

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