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A NEW RHEOLOGICAL MODEL FOR CONCRETE STRUCTURAL ANALYSIS*

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Long time deformation is of interest in estimating stresses of the prestressed concrete reactor vessel, in predicting cracking due to shrinkage or thermal dilatation, and in the design of leak-tight structures. Many interacting influences exist among creep, shrinkage and cracking for concrete. Creep and shrinkage produce or relax the stresses which cause cracking, and cracking in turn changes the stress state which causes creep. The interaction is further complicated by the influence of the aging of concrete (due to hydration) on its creep properties.

An interaction which researchers have long observed, is that at simultaneous drying and loading, the deformation of a concrete structure under the combined effect is larger than the sum of the shrinkage deformation of the structure at no load and the deformation of the sealed structure. The excess deformation due to the difference between observed test data and conventional analysis is regarded as the "Pickett Effect" (Fig. 1a). This superposition problem is compounded when simultaneous heating comes into play. It may become critical in scenarios of nuclear accidents where concrete containment is subjected to high temperature and loading at the same time.

A constitutive relation explaning the "Pickett Effect" and other similar superposition problems, which includes creep, shrinkage (or thermal dilatation), cracking, aging was developed with an efficient time-step numerical algorithm [1]. The total deformation in the analysis is the sum of strain due to elastic deformation and creep, cracking and shrinkage with thermal dilatation. Instead of a sudden stress reduction to zero after the attainment of the strength limit, we consider gradual strain-softening of concrete, i.e. a gradual decline of stress at increasing strain. This is based on the studies of fracture test data and some recently obtained tensile strain-controlled experiments. In addition, the relation between stress σ and cracking strain in the analysis is defined by a secant modulus, which is a function of cracking strain. For a uniaxial tensile stress-strain relation, the secant modulus is assumed as $C(\xi) = E_s \exp(-c\xi^s)$, where c, s, E_s are empirical constants. Based on the Maxwell chain rate-type creep law [1] we obtain a pseudo-elastic incremental stress-strain relation for finite element analysis, as follows:

$$\Delta\varepsilon = D\ \Delta\sigma + \Delta\varepsilon'' \ , \tag{1}$$

where $\Delta\varepsilon$ represents the increment of total strain; D represents the overall incremental compliance composed of a pseudo-elastic incremental compliance for the Maxwell chain and a softening spring; and $\Delta\varepsilon''$ represents the overall inelastic strain increment. In particular, the rate change of shrinkage and dilatation is given by $\dot{\varepsilon}^0 = \kappa\dot{h} + \alpha\dot{T}$, where κ, α are the shrinkage coefficient and the thermal expansion coefficient, respectively; h, is the pore relative humidity and T is the temperature of the concrete. It was concluded in Ref. 1 that both κ and α are stress-dependent. Given that the dependence on the stress σ is linear, the general form of κ and α are

$$\kappa = \bar{\kappa}\ (1 - r\sigma), \qquad \alpha = \bar{\alpha}\ (1 - \rho\sigma), \tag{2}$$

where $\bar{\kappa}$, $\bar{\alpha}$ are stress-independent coefficients and r, ρ are constants.

The result shown in Fig. 1b gives the fitting of test data [2] obtained by tensile and compressive concrete cylinder test using the above described analysis. The numerical analysis also shows that excess deformation of the "Pickett Effect" described in Fig. 1a can be explained through the following four significant factors, which are (1) stress-induced shrinkage (or dilatation); (2) tensile strain-softening due to progressive cracking; (3) irreversible unloading after tensile strain softening; and (4) increase of material stiffness due to aging. This analysis is a significant achievement in the explaning the age-old "mystery" of the "Pickett Effect". This new formulation makes it possible to achieve a realistic structural response from input parameters obtained by fundamental experimental tests (e.g. shrinkage test, basic creep test, etc.). Furthermore, this analysis is necessary in helping to understand and predict the response of concrete structures under some severe environmental conditions hypothesized in nuclear reactor containment design.

Acknowledgement

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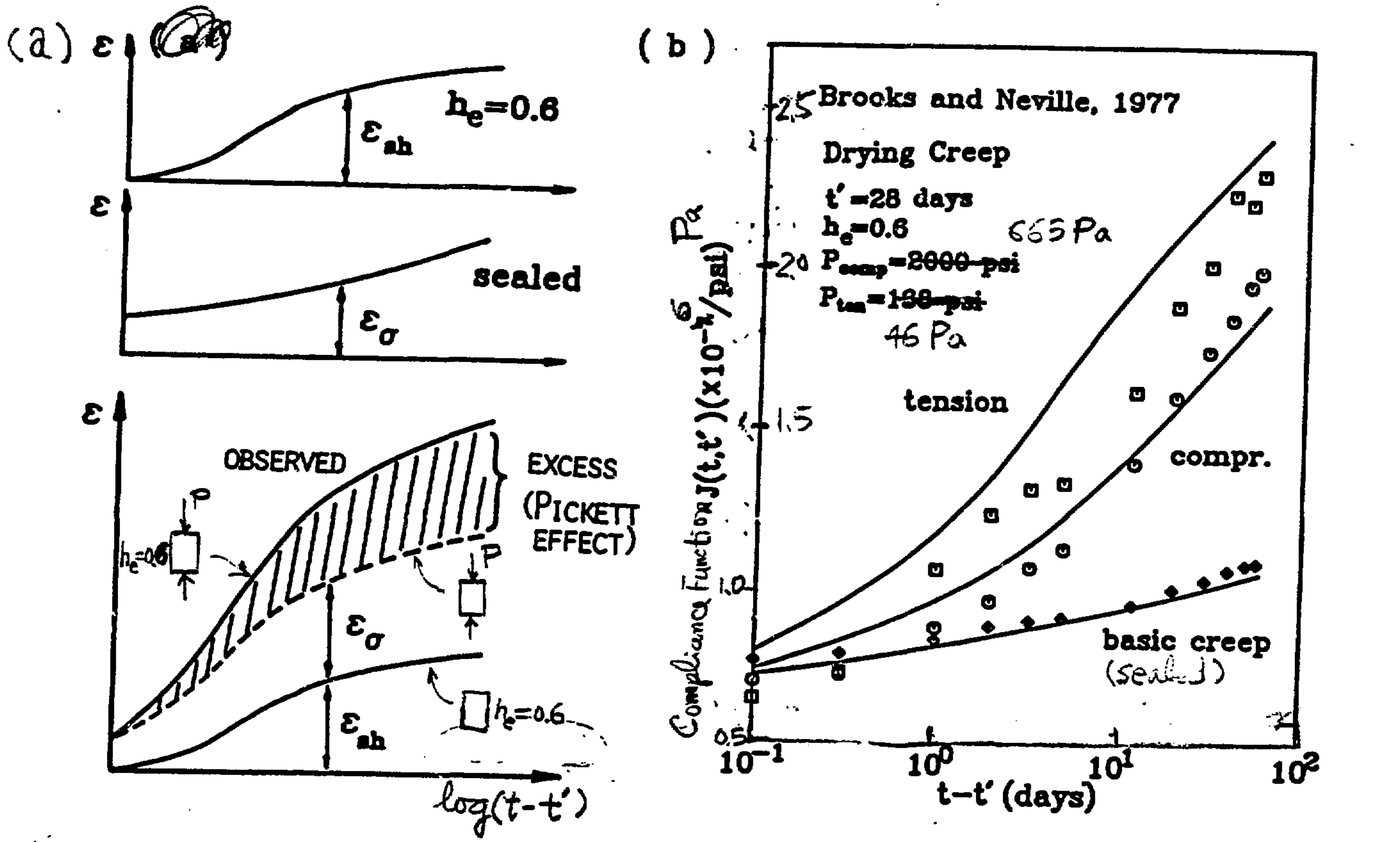

Fig. 1 Sketch of Pickett Effect and Fit of Test Data [J(t,t') represents the strain at age t caused by a unit uniaxial stress acting since age t'.]

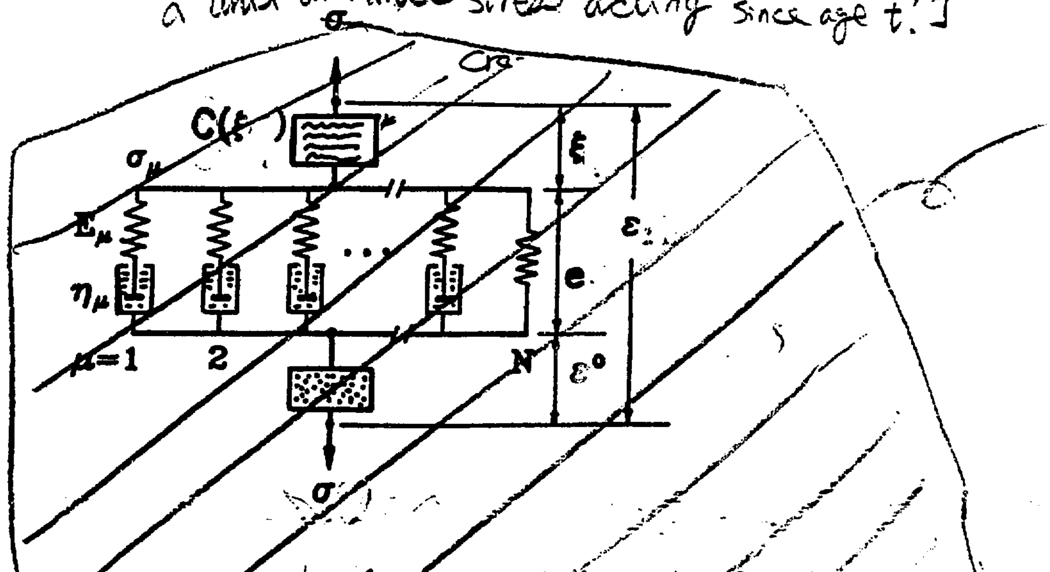

Fig. 2 Rheologic Model with Cracking