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Stress prediction in very early-age concrete subject to restraint under varying temperature histories

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ABSTRACT

Assessing the stress development in concrete requires an appropriate tensile creep model which is capable of incorporating the effect of the field environment conditions. This study quantifies the effect of temperature variation on the very early-age stress developments in restrained concrete by adopting a modified microprestress-solidification (MPS) theory-based creep model. The MPS creep model is first calibrated and verified based on the measured direct tensile creep data under normal and high temperature histories, it is then used to predict the very early-age stress development of the fully restrained concrete specimens under variable temperature history since casting. The predicted results are in good agreement with the experimental results. The tensile stress in restrained specimens can be relaxed by 80 %–87% within the first three days since casting. The predicted stress exhibits an obvious deviation from the measured one if temperature effect is not considered. Therefore, it is of importance to consider the temperature effect on concrete creep when the temperature variation in concrete is significant, and MPS creep model is valid for tensile stress prediction in concrete at very early ages.

1. Introduction

Concrete normally undergoes volumetric changes due to chemical reactions, moisture exchange and temperature variation [1,2]. Once this volumetric change is restrained, stress will develop in concrete structures. Since the early-age concrete has a relatively low tensile strength, cracking will occur when the tensile stress exceeds the tensile strength, leading to durability problems. It is well known that the stress condition in concrete structures is influenced by complex interactions of elastic modulus, creep, thermal and shrinkage deformation, and the degree of restraint [3]. Among these factors, creep property plays a significant role especially for early-age concrete. Assessing the stress development in concrete requires an appropriate tensile creep model capable of representing the field condition.

Researches concerning concrete creep can date back to about one century ago [4]. Although many achievements have been made up to date [5], attempts to predict the creep property of concrete have never ceased [6–8] due to the fact that the creep mechanism is far from fully uncovered. The existing researches show that the testing temperature influences the concrete creep remarkably. Most researchers have found that concrete creep will increase with the increasing temperature [9–12]. Briffaut et al. [13] compared the compressive strains measurements in concrete specimens under different temperature conditions, and concluded that the creep strain obtained at 60 °C is close to twice of that measured at 20 °C. Zhao et al. [14] investigated the effect of curing temperature on the compressive creep behavior of fly ash concrete, the experimental results showed that the specific creep measured under the curing temperature of 50 °C is 119.5% of that under the temperature of 20 °C for the concrete with 40% fly ash dosage. The above researches indicate the complexity of the temperature effect on concrete creep and it is necessary to take the temperature effect on creep property into consideration when dealing with the stress calculation in early-age concrete. However, investigations about the temperature effect on concrete tensile creep property are found rare. Since the temperature variation may be significant in early-age concrete due to the cement hydration and the heat exchange between the concrete and the environment, it is of importance to incorporate the temperature effect into the tensile creep model.

One of the most advanced model for creep prediction is established based on the microprestress-solidification (MPS) theory [15,16]. The solidification part of MPS theory attributes creep aging to

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the increasing volume fraction of non-aging hydration products. The microprestress part of MPS theory takes the temperature and humidity effects into account through a tensile microprestress acting across the slip planes in nanostructure of cement paste. Temperature and humidity changes will cause imbalanced chemical potential, and thus the microprestress and the change of creep rate.

This study is aimed to quantify the temperature effect on concrete tensile creep based on the microprestress-solidification (MPS) creep model. The tensile creep of early-age concrete under different temperature histories (constant normal and high temperature; temperature increase upon and during loading) was measured, and the applicability of MPS theory-based model to tensile creep modeling is verified. To reflect the characteristics of early-age concrete, the aging viscoelastic compliance term in the original MPS model is adjusted. Then the modified model is applied to predict the stress development in the fully-restrained concrete specimens. A comparison between the predicted and the measured restrained stress is discussed, which strongly stresses the importance of temperature effect on early-age concrete creep and the tensile stress developments.

2. Theoretical basics

2.1. Original MPS theory-based creep model

The microprestress-solidification (MPS) theory [15,17] is currently one of the most widely accepted and used theories for concrete creep modeling. The solidification theory part [17] provides the physical descriptions of the creep aging mechanism by assuming that aging is attributed to the volume fraction increase of the non-aging hydration products. The solidification part has been derived into a B3 model, which is widely used for compressive creep modeling of mature concrete [18]. A step further was made on solidification part by considering the influence of internal temperature and relative humidity changes of concrete on its creep development through a microprestress. Microprestress is assumed to be a normal stress acting across the slip planes represented by the hindered adsorbed layer in the nanostructure of cement paste. The change in relevant viscous termε^f is a matter of shearing slides (whether the force is tension or compression). From this perspective, there is no difference in terms of the physical background of microprestress between the compressive creep and the tensile creep loadings. Changes in temperature and relative humdity create an imbalance in the microprestress which reduces bonding between the microstructure layers and thus increases creep rate [10,15].

For the numerical modeling, the total strainε of a concrete under a constant load σ is the summation of the five components as shown in Fig. 1:

$$\varepsilon = \varepsilon^i + \varepsilon^{ev} + \varepsilon^f + \varepsilon^{sh} + \varepsilon^T \tag{1}$$

where, ε^i is the instantaneous strain; ε^{ev} is the visco-elastic strain; ε^f is the viscous strain; ε^{sh} is the shrinkage strain due to relative humidity change; ε^T is the thermal strain due to temperature change. The instantaneous strain can be expressed as:

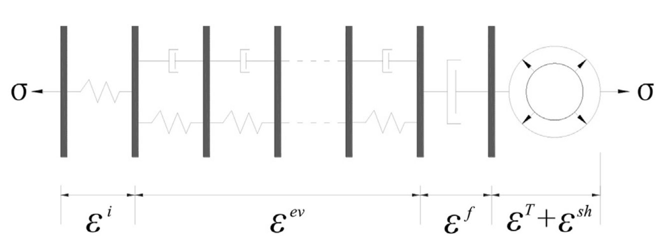

Fig. 1. Strain components characterized by a rheological model.

$$\varepsilon^i = q_1\sigma \tag{2}$$

where, q_1 is a constant which does not vary with ages within a certain temperature range of 20–70 °C under sealed conditions [10,19].

Solidification theory relates creep aging to the hydration evolution by considering the aging as the volume increase of the hydration product of C-S-H which does not age and shows visco-elastic properties. And thus, ε^{ev} in Eq. (1) can be written as:

$$\dot{\varepsilon}^{ev}(t) = \frac{\dot{\gamma}(t)}{v(t)} \tag{3}$$

$$\gamma(t) = \int_0^t \Phi(t-\tau)\dot{\sigma}(\tau)d\tau \tag{4}$$

where, $\Phi(t-t') = q_2\ln(1+\xi^n)$; $\xi = (t-t')/\lambda_0$; $v(t)^{-1} = (\lambda_0/t)^m + \alpha$; $\alpha = q_3/q_2$;$n = 0.1$ $m = 0.5$; $\lambda_0 = 1d$; $v(t)$ is the volume fraction of hydration products or solidified materials; $\gamma(t)$ is the visco-elastic strain of the hydration product of C-S-H, which is non-aging and can be fully recovered after unloading; q_2 (in MPa^{-1}) and α(dimensionless) are the fitting parameters.

The viscous term ε^f in Eq. (1) is not recoverable, which can be represented by a dashpot (Fig. 1) with the following expression:

$$\dot{\varepsilon}^f(t) = \frac{\sigma(t)}{\eta(S)} \tag{5}$$

where, $\eta(S)$ is viscosity of the dashpot and is a power function of microprestress S, $1/\eta(S) = cbS^{b-1}$. S is normally greater than the externally applied stress. Along with the capillary and adsorption forces which dominate the stress levels in microstructure, the total stresses in microstructure far exceed any stresses that can be produced by the externally applied load [15]. The microprestress forms upon the formation of the microstructure and relaxes over time. The changes of the internal relative humidity and the temperature of concrete will increase microprestress. The evolution of the microprestress is assumed to follow Maxwell-type rheological model [15,16]:

$$\frac{\dot{S}(t)}{C_S} + \frac{S(t)}{\eta(S)} = \frac{\dot{s}(t)}{C_S} \tag{6}$$

where, $\dot{s}(t)/C_S$ is the strain rate of Maxwell model. For the case of basic creep without temperature changes, the right hand side of Eq. (6) can be assumed to be zero, and thus Eq. (6) is solved in a closed form:

$$S(t) = \left\langle S_0^{1-b} + c_0(b-1)(t-t')\right\rangle^{1/1-b} \tag{7}$$

S_0 is the initial value of $S(t)$. Thus, Eq. (5) becomes:

$$\dot{\varepsilon}^f(t) = \frac{bc}{S_0^{1-b} + c_0(b-1)(t-t_0)}\sigma(t) \tag{8}$$

where, $c_0 = C_S cb$; $S_0^{1-b} = (b-1)c_0 t_0$; $b = 2$. Let $q_4 = bc/[c_0(b-1)]$, Eq. (8) becomes:

$$\dot{\varepsilon}^f(t) = q_4\sigma(t)/t \tag{9}$$