Construction and Building Materials 147 (2017) 203–211

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Nonlinear model for early age creep of concrete under compression strains

Bing Han [a,b,*], Hui-Bing Xie [a], Li Zhu [a], Peng Jiang [a]

[a] School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China
[b] Key Laboratory of Safety and Risk Management on Transport Infrastructures, Ministry of Transport, PRC, Beijing 100044, China

HIGHLIGHTS

- A viscoelastic–plastic creep model for early age concrete creep prediction was established.
- The acoustic emission test was conducted to identify any damage that might have occurred during creep.
- Experiment on the nonlinear creep of early-age concrete was carried out.

ARTICLE INFO

Article history:
Received 16 August 2016
Received in revised form 11 April 2017
Accepted 14 April 2017
Available online 28 April 2017

Keywords:
Early age concrete
Creep
Nonlinearity
Rheological model
Acoustic emission

ABSTRACT

Creep of early age concrete is more significant than that of hardened concrete, and it is possible that early age concrete creep presents nonlinearly because of high stresses imposed during construction. In this paper, a viscoelastic–plastic model was proposed to simulate early age concrete creep. Experiments of early age creep of concrete under different stresses, have revealed the nonlinear features of specimens under high stresses. Acoustic emission (AE) technology was applied to collect damage information of early age concrete during creep, and the relationship between the degree of damage and increments of nonlinear creep was deduced according to test data. The parameters involved in the model were regressed. Also, a modified B3 model was proposed to consider nonlinear creep increments of concrete. It can be conclude that the item concerning concrete damage in the proposed model is important for predict the nonlinearity of early-age concrete creep, and it can be used to modify existing models.

1. Introduction

Creep is an important time-dependent behavior of concrete and can result in adverse effects, such as increasing deformation, redistributing stress and internal force, and even structural failure [1,2], on structures. To most concrete structures, creep effects caused by early age loading are universal, and early age creep is more significant than creep in hardened concrete [3–5]. Because early age concrete is immature, and with rather low strength, relatively high stress levels would be imposed on the concrete, and early age creep would present nonlinear features [6,7], which would not adhere to the Boltzmann superposition principle.

Existing research on early age concrete creep has focused more on issues concerning concrete under tensile stress caused by shrinkage and temperature rather than concrete under compressive stress. In practice, cases of concrete subjected to compressive stress at early ages are common, e.g., concrete dams, continuous beams constructed by cantilever methods, high-rise piers, and concrete-filled steel tubular arch bridges constructed by non-bracket methods. It should be noticed that different developing rules were found between the tensile and compressive creep of early age concrete [8].

Under high stress levels, creep sourcing from micro-cracks in concrete should be recognized as nonlinear [9]. In early age concrete, the volume of cement hydration products increases sharply with time, and porous structures in cement gel change violently. Mechanisms of nonlinear creep in early age concrete require additional study [10]. Another important topic is whether existing macroscopic creep models (*fib* 2010 [11], B3 [12], ACI 209 [13], GL2000 [14]) and mesoscopic models [15–17] suitable for prediction of creep can be used to describe nonlinear features. Models formed on the basis of the superposition principal do not meet the requirement.

If the nonlinearity of creep from damages in concrete is substantiated, the difficulty lies in how to quantify the damage during

* Corresponding author at: School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China.

E-mail address: bhan@bjtu.edu.cn (B. Han).

http://dx.doi.org/10.1016/j.conbuildmat.2017.04.119
0950-0618/

creep. In the past 30 years, acoustic emission (AE) technology has been widely used to detect damages in structures [18–24]. Its operating principle is that, once damage occurs in the concrete, elastic waves are produced concomitantly and can be detected by acoustic receiving sensors. After which, real-time corresponding relations between the damage and the sound signals received can be determined. Some studies have focused on the use of AE technology testing on concrete creep [9,25–27]. It is possible that the technology can be used to detect the evolution of damage during creep.

This paper aims at discovering the developing rules of early age creep in concrete under different stress-strength ratios. Rheological theory was used to develop a viscoelastic–plastic model for early age concrete creep. Based on the test data and relationship between damage and nonlinearity of creep, a modified B3 model was proposed. Early age concrete creep under different stresses were tested, and AE technology was used to obtain damage information in concrete during creep. The relationship between concrete damage and nonlinearity of creep was suggested, and it is valuable to recognize the mechanism of nonlinearity of creep in concrete under high stress.

2. Viscoelastic–plastic model for early age concrete creep

2.1. Model formation

Through the assembly of models by various rheological components, which can characterize the basic properties of materials, such as elasticity, viscoelasticity, viscidity, or damage, a comprehensive performance of materials could be depicted. At present, these kinds of models have been widely used to simulate creeps in rocks [28], asphalt [29], and high-polymer materials [30], as well as concrete [31].

In general, the creep strain of concrete can be divided into three parts: elastic strain, recoverable viscoelastic strain, and unrecoverable viscous strain [1]. For early age concrete, unrecoverable visco–plastic strain likely occurs from damages induced by high stress levels. Therefore, an early age creep model can be established by assembling the following rheological components. In the model, the elastic- and visco strain are represented by a Maxwell model that consists of a spring with stiffness E_1 and a damper with the rheological coefficient of η_1 in a series (see ① and ②, Fig. 1); the viscoelastic strain by Kelvin model, combined with the parallel connection of a spring E_2 and a damper η_2 (see ③ and ④, Fig. 1); and visco–plastic strain by a Bingham model combined with the parallel connection of a damper η_3 and a Saint-Venant body σ_{vp} (see ⑤ and ⑥, Fig. 1).

As stated, concrete would be damaged under relatively high stresses and its creep strain presents nonlinearly. In this model, the Bingham model was included to feature the nonlinear aspect of the early age concrete creep. If stresses exceed σ_{vp} of the Saint-Venant body, which signifies damage, the Bingham model takes its effect, or else its strain is zero.

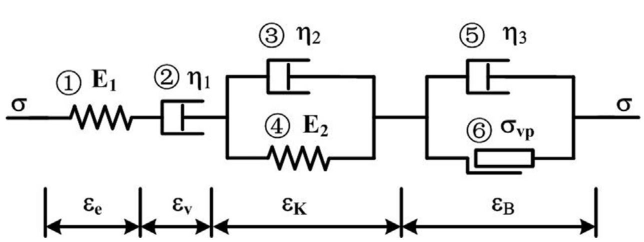

Fig. 1. Formation of a viscoelastic–plastic model for early age creep of concrete.

2.2. Parameter determination

Herein, the strain of the Maxwell model under stress of σ can be expressed as

$$\varepsilon_M = \varepsilon_e + \varepsilon_v = \frac{\sigma}{E_1} + \int_{t_0}^{t} \frac{\sigma}{\eta_1} dt, \tag{1}$$

in which, ε_M, ε_e, and ε_v denote strains of the Maxwell model, and spring ① and damper ② under stress σ, correspondingly; ε_e and ε_v can be determined by elastic strain and unrecoverable strain, respectively.

Strain of the Kelvin model can be expressed as

$$\varepsilon_K = \frac{\sigma}{E_2}\left(1 - e^{-\frac{t-t_0}{\tau}}\right), \tag{2}$$

in which, ε_K denotes strain of the Kelvin model, which can be measured by recoverable strain in experiments; t and t_0 mean time and loading age, respectively; and τ is an effective time coefficient, $\tau = \frac{\eta_2}{E_2}$.

The stress–strain relationship of the Bingham model depends on whether the Saint-Venant body is triggered and can be expressed as

$$\varepsilon_B = \begin{cases} 0 & \sigma \leqslant \sigma_{vp} \\ \int_{t_0}^{t} \frac{(\sigma - \sigma_{vp})}{\eta_3} dt & \sigma > \sigma_{vp} \end{cases} \tag{3}$$

in which, ε_B is strain of the Bingham model, related with damages occurred during creep; σ_{vp} is critical stress to trigger the Saint-Venant body.

In summary, the total strain of the early age creep could be obtained by

$$\varepsilon = \varepsilon_M + \varepsilon_K + \varepsilon_B = \begin{cases} \frac{\sigma}{E_1} + \frac{\sigma}{E_2}\left(1 - e^{-\frac{t-t_0}{\tau}}\right) + \int_{t_0}^{t} \frac{\sigma}{\eta_1} dt & \sigma \leqslant \sigma_{vp} \\ \frac{\sigma}{E_1} + \frac{\sigma}{E_2}\left(1 - e^{-\frac{t-t_0}{\tau}}\right) + \int_{t_0}^{t} \frac{\sigma}{\eta_1} dt + \int_{t_0}^{t} \frac{(\sigma - \sigma_{vp})}{\eta_3} dt & \sigma > \sigma_{vp} \end{cases} \tag{4}$$

3. Experimental investigation

Two groups of early age concrete specimens were loaded at 2 d of age with different initial stress-to-strength ratios in the experiment. Each group was unloaded completely at different ages to explore the time dependence of concrete viscoelasticity. AE tests of the loaded specimens were performed to quantify damages that occurred during creep.

3.1. Materials and specimen preparation

3.1.1. Raw materials and mix proportion

Ordinary Portland cement, 42.5 MPa strength, was used in the experiment; its chemical components are given in Table 1. Coarse aggregates used gravels with continuous grading from 5 to 25 mm, and sand diameters were from 0.15 to 4.75 mm and with a fineness modulus of 2.6. The mix proportion of the concrete is given in Table 2.

3.1.2. Specimen description

The specimens are prism-shaped and 100 × 100 × 300 mm in size. All of the specimens for the creep test were 2 days old when loaded and were separated into two groups. The specimens in one group were loaded with stresses of 18, 39, 58, and 76% of concrete strength at 2 days old, respectively, and were unloaded on the tenth day after loading. Those in the other group were loaded with stresses of 38, 55, and 74%, respectively, and were unloaded on the 25th day after loading, as listed in Table 3. According to the tests on