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Long-term deformational simulation of PC bridges based on the thermo-hygro model of micro-pores in cementitious composites

Koichi Maekawa *, Nobuhiro Chijiwa, Tetsuya Ishida

Department of Civil Engineering, The University of Tokyo, Japan

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ABSTRACT

Creep deflections that greatly exceed the predicted values by the linear creep law are being found in measurements on actual PC bridge viaducts. In this study, structural creep deformations were reproduced by using the multi-scale coupled thermo-hygro and mechanical modeling which enables to deal with an interaction of chemo-physical events of differing dimensions ranging from the kinematics of moisture in micro-pores to the macroscopic structural mechanics, and the effect of various factors was analytically investigated. The numerical analysis approximately reproduced the excessive deflection measured on an actual bridge viaduct. It was confirmed that the creep bending of the viaduct having the hollow cross-section varies significantly due to the ambient temperature, humidity and the structural specific surface area. The macroscopic structural responses in association with the thermodynamic state of moisture in the micro-pores are also discussed.

1. Introduction

In all parts of the world, excessive deflection that greatly exceeds the design values has been reported for PC bridge viaducts that have been constructed for more than 20 years [1–4]. Most of these bridges were constructed around 1975 and were designed in use of the linear creep law that assumes the evolution of creep strains 2–3 times the elastic strains. However, back calculating from the actual deflection on the bridge viaducts, the linear creep coefficient of around 4–5 is inversely obtained [5,6], which is more than double the value measured in laboratories and used in design guides of each country [7–9]. Although creep and drying shrinkage of concrete specimens can be estimated with high accuracy, there is much scope for improvement in the prediction of long term deformation of actual structures. For the maintenance management of existing PC bridges, it is essential to be able to determine whether the long term flexure will converge or not, as well as when and to what value, based on scientific grounds.

The apparent creep of concrete specimens depends on the micro-pore structure of the hardened cement paste and the thermodynamic state of moisture trapped in the pores. Hardened cement paste is formed as a collection of pores of various sizes, ranging from relatively coarse capillary pores to interlayer pores on the scale of water molecules. The kinematics of moisture in micro-pores and the deformational behavior of cement hydrates that form gel and capillary pores vary greatly depending on the scale of the pores. To construct a time-dependent deformational model of cementitious composites, it is necessary to take into account the different deformational characteristics of each of the microstructural units.

The authors have developed a 3-dimensional material–structure coupled analysis (abbreviated as *DuCOM-COM3*) [10] that tracks the time history of the variation in long term properties of concrete structures from production stages to the end of its service life. By running in parallel a thermodynamic coupled analysis that numerically models hydration reactions, pore structure formation, moisture migration in a coupled manner (nm to μm), and a material–structure response analysis (mm to meter scale) based on a nonlinear material constitutive law while sharing digital information successively, it is possible to follow the phenomena (Fig. 1). By integrating the phenomena of moisture movement and solid–liquid equilibrium within micro-pores of different dimensions, a constitutive model that can be applied to volumes ranging from “cm” to “meter” scales can be constructed [11,12]. It is possible to evaluate macroscopic structural deformation or cracking damage, etc., caused by the phenomena at the scale of water molecule, such as internal stresses due to capillary tension or surface energy. The moisture transport through micro-pores of cement hydrates is simulated in terms of the vapor diffusion and the convection of condensed water [10,31] as shown in Fig. 1.

Here, the vapor pressure as the primary variable for the molecular diffusion is computed so as to satisfy the thermodynamic equilibrium with the condensed water stored in micro-pores with non-uniform pore-size distribution. After the cracking in structural concrete, the moisture transport is accelerated since the additional paths surrounded by crack planes are created. This coupling effect of the structural damage on the micro-thermodynamics is automatically

* Corresponding author. Fax: +81 3 5841 6010.
E-mail address: Maekawa@concrete.t.u-tokyo.ac.jp (K. Maekawa).

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