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Three-dimensional micromechanical modeling of concrete degradation under multiphysics fields

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ABSTRACT

Concrete is a typical composite material including multiple phases. Concrete however is commonly treated as a homogeneous material in structural designs for the calculation of stress and strain. Moreover, concrete structures in service are subject to various mechanical and environmental loads. In design practices, these loads are handled separately without considering their interactions that could cause accelerated material degradation and unsafe designs. This work presents a finite element method (FEM) based model developed for studying concrete degradation by the synergistic interactions of applied mechanical and environmental loads with due consideration of the 3D microstructure of concrete that is reconstructed using the X-ray computed tomography (CT) technique. The degradation of a roadway concrete slab was simulated using the developed model. The results show that the microstructure of concrete matrix plays an important role in the distributions of stress and strain in concrete and that the effects of moisture and temperature in concrete are significant comparing to the effect of wheel load. This 3D microstructural multiphysics model can be used for design and non-destructive assessment of concrete structures of special shapes and needs, e.g., nuclear reactor vessels, which have high complexity and require high accuracy.

1. Introduction

Concrete is the world's leading construction material owing to its great economy, high strength, and long-term integrity [1–3]. For proper utilization of concrete in construction, it is important to adequately characterize the mechanical and general chemo-physical properties of concrete, including its compressive and tensile strength, non-linear elasticity and plasticity, cracking resistance, creep and shrinkage, as well as its thermal and transport properties and chemical resistance. Improper characterization of concrete materials may cause a biased design that is either uneconomical or structurally unsafe [4–6]. The adequate characterization of concrete properties however cannot be accomplished without due consideration of the complex microstructure of concrete matrix. The heterogeneous concrete matrix contains two major solid phases, hydrated cement paste and aggregate, with quite different properties that could affect the stress and strain distribution inside concrete. The physicochemical interactions between aggregate particles and those between the aggregate phase and hydration products of cement can play important roles in determining the stress and strain levels in concrete. Treating concrete as a homogeneous material, as commonly practiced in the design of concrete structures, can be upgraded to microstructural-based designs to achieve more accurate designs [7].

Concrete structures are designed to support loads without excessive stress and deformation during their service lives. In practices, however, concrete frequently cracks and/or deforms excessively under combined mechanical, temperature, and moisture loads as is observed on roadway slabs working under typical traffic and outdoor conditions. The temperature and moisture loads often induce slab curling and warping, which can add to the wheel-load caused deflection to cause high enough curvature and lead to concrete cracking. From this standing point, appropriate consideration of the synergistic effects of the multiple physics fields is equally important in concrete designs with improved accuracy. Mechanical load, temperature field and moisture field are the three physics fields executed on general concrete structures. Coupling of these three fields in a design process thus has broad impacts. The determination of stress, strain and deformation due to mechanical load can be accomplished using continuum mechanics based on determined materials properties such as elastic and plastic moduli and

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Poisson's ratio [8,9]. The variation of temperature in a concrete structure is governed by the Fourier's law and the determination of temperature distribution is necessary for quantifying concrete curling (based on parameters of heat transfer and thermal expansion) [8–10]. The coefficient of thermal expansion of concrete has been used for determining the temperature-gradient induced strain; this strain can then be coupled with the mechanical strain caused by the self-weight and truck wheel loads. Modeling of moisture-induced deformation in concrete in more complicated than thermal deformation. Moisture-induced deformation is related to the coefficient of the hygroscopic swelling and shrinkage of the concrete material. Moisture transportation through variably saturated concrete (saturated and unsaturated) is a complex process related to negative pressure, saturation level and geometry of concrete [11,12]. The moisture-gradient induced strain when determined needs to be coupled with the mechanical strain and temperature strain to determine the total strain in concrete.

Numerical simulation has been commonly used in investigating the behavior of concrete under combined physics fields [8,9,13]. Wang et al. conducted a simulation to investigate the temperature effect on a concrete bridge using finite element method [10]. Granger et al. proposed a simple experimental method based on hypothesized curves of drying shrinkage (as a function of weight loss) and validated the hypothesis on the basis of a probabilistic model of concrete cracking [11]. Chen and Mahadevan developed a numerical formulation using finite element method (FEM) for simulating cracking in concrete [13]. The thermal transfer and moisture transport were coupled to study a plain and homogeneous concrete material. Pan and Wang proposed a concept of concrete-water characteristic curve (CWCC) to describe unsaturated concrete [7]. Lorensen and Cline presented a new algorithm, marching cube, for reconstructing 3D model and achieved a successful application in clinical diagnoses [14]. In the open literature, however, little research has been conducted to study concrete degradation under combined mechanical, temperature and moisture effects with the microstructure of concrete materials properly considered.

2. 3D reconstruction of concrete microstructure

X-ray computed tomography (CT) was initially used in the application of non-destructive medical anatomy to recover the internal structure of a subject [15]. As the popularity in 3D image reconstruction increases, many reconstruction approaches were investigated to accomplish an accurate reconstruction of a 3D object from a series of 2D CT images that characterize the internal structure of the object. This study presents an algorithm to reconstruct the 3D microstructure of a heterogeneous concrete slab using X-ray CT images, of which the reconstruction process consists of three major steps as shown in Fig. 1. This algorithm entails first rebuilding 3D voxel elements from 2D pixel elements of the CT 2D images and then assembling the voxels to form the targeted 3D microstructure object, i.e., the concrete slab [16].

The first step of the 3D reconstruction is the digitalization of the series of gray-scale 2D X-ray CT images that essentially are a digital description of the images using a mathematical matrix. Each pixel of a gray-scale image has an intensity value varying from 0 to 255 (called gray value) indicating that brightness vary from the completely dark (0) to the brightest (255). Such a mathematical matrix with its intensity values can also be used to indicate 3D voxels extruded from the 2D pixels. Fig. 2 schematically descripts the process of digitalization of a CT image and the voxel elements extruded from the mathematical matrix.

The second step of the 3D reconstruction consists of defining a global coordinate system and assigning connectivity between the voxels. Using the defined coordinate system, each of the eight nodes of a 3D voxel (a hexahedron) element has a definitive location in the global system after the connectivity is assigned. The interval value of each node depends on the dimension of the eight-node hexahedron element as shown in Fig. 3. In Fig. 3, the letters i, j, and k are the three orthogonal coordinates of each voxel

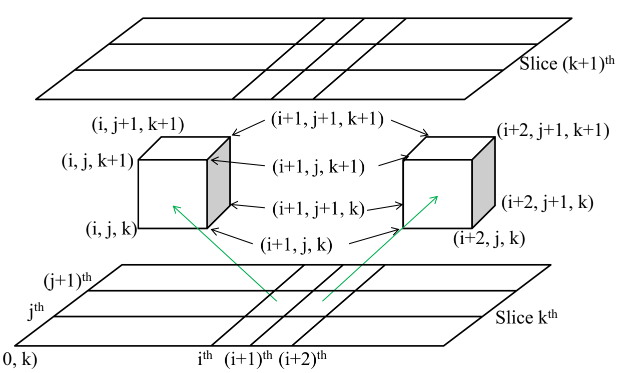

Fig. 3. Definition of global coordinate system and assignment of connectivity among voxel elements.

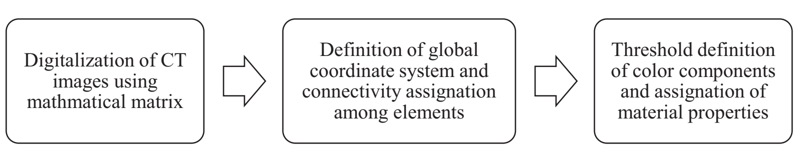

Fig. 1. Procedures of 3D reconstruction of concrete microstructure.

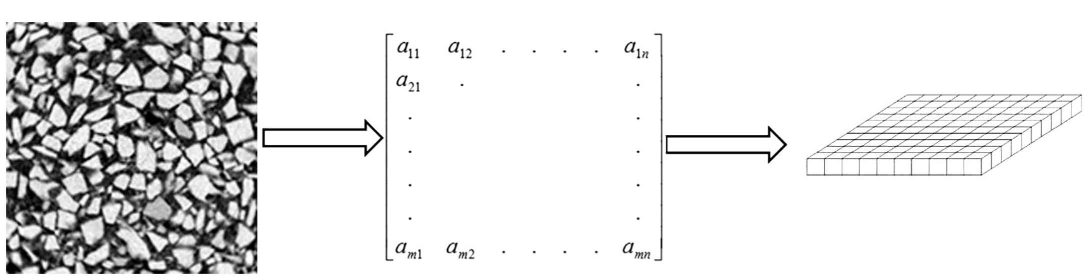

Fig. 2. Digitalization of a 2D CT images and construction of a layer of 3D voxel elements.