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Mesoscale simulation of cement based materials' time-dependent behavior

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Abstract

A numerical mesoscale model for the characterization of creep and shrinkage of cement based materials is evaluated. It is the first mesoscopic model for cement-based materials time-dependent behavior. The analytical part of model is developed using Solidification Theory, Kelvin type rheological models, and Dirichlet Series. Concrete is modeled as three phased composite system. The aggregate shape and grading is designed by the written program according to American Standards. The whole concrete cross-section is simulated by using lattice type modeling algorithm. Numerically generated concretes creep and shrinkage behaviors are evaluated and cross section of the specimen is reshaped. Thus, the behaviors of each three phases are observed according to aggregate type, shape, and grading, cement content and ingredients, water, temperature, cross-section, and volume of whole concrete. The simulation results are confirmed some of the existing theories and provided new information on concrete creep and shrinkage.

Keywords: Creep; Shrinkage; Lattice modeling; Mesoscale; Time-dependent behavior

1. Introduction

Concrete is a multiphase exceedingly complex heterogeneous material and experiences volume changes throughout its service life. The volume change of concrete is the resultant of applied loads, shrinkage, and cement hydration, which continues over the years. Realistic prediction of time-dependent behavior of concrete is of crucial importance for durability and long-time serviceability of concrete structures. Mispredictions of this phenomenon, which result in the excessive deflections and cracking, have been one of the reasons for problems with longevity of the civil engineering infrastructure in all countries [1,2].

A concrete specimen also experiences volume changes throughout its life time even in the absence of applied loads. This deformational change is called shrinkage, which is generally defined as volumetric or dimensional decrease. Specifically, shrinkage is strain measured on a load free specimen [3].

Hydration, the chemical reaction between water and ingredients of cement is one of the most important properties of its time dependency. This property of hydration process causes volume change of hydrated cement, varying hydration rate through the concrete and time dependency of strength gain. Shrinkage occurring in a specimen that is exposed to the environment and allowed to dry is called drying shrinkage. Drying shrinkage involves moisture movement through the material and moisture loss. Whenever the shrinkage occurring in the absence of moisture exchange (as in a sealed concrete specimen) due to the hydration reactions taking place inside the cement matrix is termed autogenous shrinkage. Autogenous shrinkage was almost never considered as a factor in research on shrinkage and creep before 1990, and it has become a greater factor with the increased use of high-performance concrete [3]. The other

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types of shrinkage (plastic shrinkage and carbonation shrinkage) are outside the scope of this work.

Creep represents the time-dependent strain increase under sustained constant load taking place after the initial strain at loading. Creep strain may be subdivided into a drying and a non-drying component, termed drying, and basic creep, respectively. Basic creep is the time-dependent increase in strain under sustained constant load of a concrete specimen in which moisture losses or gains are prevented. Drying creep is the additional creep occurring in a specimen exposed to the environment and allowed to dry [3]. So, the main difference between creep and shrinkage is applied load existence or not.

When time-dependent behavior of concrete is considered, the non-linear viscoelastic behavior has to be modeled. The mentioned non-linearity is a way of simulating heterogeneity of cement based materials. For in-depth understanding of concrete, many type of theoretical studies are realized based on microplane theory, endocrinic theory, solidification theory, rigid particle contact model etc. [4]. It seems possible to design concretes with different strength and brittleness starting from the structure of composite at a lower level of observation of heterogeneity of concrete extends over many different size scales: it is truly multiscale material with different structural details appearing at different levels of observation [1,4,5].

When concrete is modeled, one can use traditional finite element techniques, or one may revert to lattice type models where the connection between different points in the material is modeled by means of linear elements. The lattice technique has been employed for years at the Stevin Laboratory of Delft University of Technology by Van Mier and co-workers. The detailed information about lattice type modeling techniques is given elsewhere [5–9].

When loaded, concrete experiences an instantaneous recoverable elastic deformation and a slow inelastic deformation called creep. Specifically, concrete-like time-dependent materials' behavior has great importance for structural engineering. Realistic creep and shrinkage estimations are necessary in design of reinforced concrete beams with large spans, pre-stressed concrete members, cable stayed or arch bridges, nuclear containments, shells, etc. [1–4].

All known creep and shrinkage prediction models are based on macroscopic behavior of concrete. None of them takes into account the actual shape, size, elasticity and possible failure of the aggregate particles, thickness and properties of the mortar layers between aggregate particles, and interfacial transition zone between aggregates and mortar [1,5]. It is known that, the aggregate type and content is significantly affects the creep and shrinkage deformation. But at the macroscopic level, the material is considered as a black box and no internal structure is recognized. Only some empirical approximations are used to add variable internal effects. Present work assumes the concrete as three phase material consists of aggregate, mortar, and aggregate–mortar interface at mesoscopic level. The detailed information about lattice type modeling techniques is given elsewhere [1,6,7]. This work is so far first attempt to predict creep and shrinkage deformation which includes autogenous and drying shrinkage at mesoscale using lattice technique.

2. Research significance

Creep and shrinkage have been a complex problem of research for quite some time. Realistic prediction of creep and shrinkage, which will never be possible, is a result of several interacting physical mechanisms and is influenced by many variable factors such as environmental conditions, drying in the cross-section, loading, etc. For this reason, computational algorithms and the use of computational simulation techniques in concrete applications increased rapidly in recent years. However, the accumulated advancement has been at macroscale and none of them take into account the internal components of the composite. In that case, a mesoscale modeling attempt is needed for a better prediction of cement based materials' time-dependent behavior.

3. Numerical simulation

Meso-level models have proven to be applicable for studying the influence of the concrete composition on the macroscopic properties. At this level, the material is modeled as a three-phase material consisting of the coarse aggregate particles, the surrounding mortar matrix and the interfacial transition zones between them. Phenomenological models describing the concrete as a homogeneous material nowadays are allowed realistically simulating fracture processes but are not accounted for the effects of the concrete composition on the macroscopic material behavior. For obtaining a deeper understanding of the physical processes determining the macroscopic material behavior models considering the inhomogeneous nature of concrete are required [1,5,7].

The actual shape, size, elasticity and possible failure of the aggregate particles, thickness and properties of the mortar layers between aggregate particles, and interfacial transition zone (ITZ) between aggregates and mortar are the effective parameters for creep and shrinkage deformation. For a better prediction of such deformation, a well generation of aggregate, mortar, and ITZ structure is required. A generation of thought aggregate content has to be numerically generated according to Fuller curve. The heterogeneous grain structure of concrete was assumed to follow the Fuller grading curve in 2D whose details are given elsewhere [1,10].

$$\begin{aligned} P_c(D < D_0) = P_k \times (&1.065 \times D_0^{0.5} d_{\max}^{0.5} - 0.053 \times D_0^4 \times d_{\max}^{-4} \\ &- 0.012 D_0^6 \times d_{\max}^{-6} + 0.0045 \times D_0^8 \times d_{\max}^{-8} \\ &+ 0.0025 \times D_0^{10} \times d_{\max}^{-10}), \end{aligned} \quad (1)$$