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Mesomechanical model of moisture diffusion and shrinkage cracking in building material – Model development

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HIGHLIGHTS

- A mesomechanical model of moisture diffusion in building material is proposed.
- Heterogeneity is an important parameter that influences the moisture diffusion.
- The diffusivity increases when there is a crack growth.
- The existence of ITZ leads to significant increment of moisture migration.

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ABSTRACT

Drying shrinkage of concrete induces the formation of microcracks that damage concrete structures. In this study, a methodology to model this phenomenon is presented which is simple and easy to implement and should enable engineers to predict shrinkage cracks by taking them as a durability indicator. We first present how to theoretically and numerically implement a two-dimensional model to examine meso- and macroscopic structure effects on moisture diffusivity within concretes. The heterogeneity of concrete is described by Weibull distribution assumption at a mesoscopic level. Simulations on several heterogeneous samples show that the effective diffusivity strongly depends on the degree of heterogeneity. Higher heterogeneity indicates a greater effect on the effective moisture diffusivity. Moreover, numerical results indicate that the effective diffusivity of concrete greatly depends on the volume fraction of aggregate (VFA), the increasing of which decreases the effective diffusivity. Modeling result suggests that diffusivity increases when there is a crack growth due to the damage creating more porous and thus accelerating moisture diffuse through the matrix, i.e. resulting in increment of effective moisture diffusivity. The result also indicates that the existence of interfacial transition zone in concrete also leads to significant increment of moisture migration in concrete. Furthermore, the effect of crack depth and its propagation on moisture diffusion has been studied.

1. Introduction

The mass transfer phenomenon is widespread in nature and humidity change is thought of as a migration process of moisture. Due to the difference of moisture contents between the porous media and its environment, the media absorb water from the environment when the ambient humidity is higher than that of the media boundary surface, causing the media to swell. However, if the ambient humidity is lower than that of the media boundary surfaces, the media release water to the environment, resulting in the media to shrink. When the deformation caused by humidity variation is restrained, the swelling or shrinkage stress will be generated in the structure. The change in internal stress-state of the media results in the occurrence of cracks, most of them are surface cracks. Many hydraulic and building structures involves the problem of the humidity diffusion, most of them also refer to the temperature effect simultaneously. In Northern China, for example, a great temperature difference exists between day and night. In such region, the humidity between the environment and the inner of concrete is greatly different, resulting in serious surface cracks. Especially in summer, as reservoirs running at the level of flood control, the water-saturated concrete is subjected to the role of solar radiation. This results in large amounts of shrinkage cracks in the upstream face of concrete dam, which affects the safety of the dams. In addition, when concrete is subjected to fire, the free water, the capillary water and some of absorbed water will evaporate. If evaporation rate is higher than vapor migration rate, pore pressures may develop; and if the pore pressure exceeds the tensile strength of concrete, explosive spalling may occur resulting

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in concrete to collapse [1]. Some other engineering phenomena, such as absorption of bricks [2], drying process of building slab [1], and water evaporation from the surface of freshly placed concrete, all refer to the moisture migration and the interaction between temperature and moisture. Furthermore, Lü [3] pointed out that moisture caused damage problem is one of the most important factors limiting a building service life. Therefore, the study on the humidity diffusion as well as the effect of temperature on its process is important to reveal the mechanism of swelling and shrinkage cracking. It is helpful for the safety design of structure.

In general, the moisture migration in porous media like concrete is very complex because of the different kinds of transport mechanism in combination with various types of pores that typically appears in the same porous system. Even up till today, it is still not clear which transport mechanism that takes place in the gel-pores. However, there is a general agreement that the diffusion mechanism is used to describe this transport in the porous media [4,5]. For decades, many researchers have devoted their work to modeling the moisture transfer in buildings. Macroscopic models were accepted and used to study pressure head and moisture transfer through porous media. One of them is Luikov model [6] or Phillip and de Vries model [7], which uses the temperature and moisture content as driving potentials. However, there are three main difficulties when Luikov model or Phillip and de Vries model is used to calculate the non-isothermal moisture in porous materials, i.e. (1) the moisture content profile is discontinuous at the interface between two different porous media; (2) the moisture diffusion coefficient and thermal diffusion coefficient are dependent on the two potentials which is quite difficult to determine in laboratories; (3) the highly coupled governing equations are difficult to handle [8]. In order to solve the discontinuity problem of moisture content, Pedersen [9] used the capillary pressure and Künzel [10] used the relative humidity as a potential. Milly [11] and Janssen et al. [12] have also reformulated the Philip and de Vries equations for coupled heat and moisture transfer to obtain a "porous matrix potential" rather than taking moisture content as an independent variable. Furthermore, in order to model the humidity diffusion processes, Bažant [13] and Ichikawa et al. [14] also proposed the differential equations based on the principle of conservation of mass and energy.

The researches mentioned above mostly focused on the moisture migration in porous media. However, different from those in other porous media [15,16], the change of moisture content in concrete is affected by not only the diffusion effect but also the self-desiccation. By studying the humidity distribution in concrete under isothermal drying conditions, it was shown that along with reducing water–cement ratio, the self-drying role in causing relative humidity to change turns to be enhanced while the humidity diffusion role in causing relative humidity turns to be weakened. Furthermore, the relative humidity distribution in concrete with high water–cement ratio is mainly controlled by the diffusion process, but reversely, not vice versa, that with low water–cement ratio is not only controlled by the moisture diffusion but also affected by the self-drying [16]. In order to consider temperature effect on moisture migration, Martín-Pérez et al. [17] proposed a method in which the transport of moisture, oxygen and the convection of heat were described by the modified versions of Fick's second law of diffusion and thus the generated PDEs had all the same order and mathematical structure. Puatatsananon [18] and Saetta [19–21] proposed mathematical models for coupling temperature and humidity within concrete which as well provides a theoretical solution to study the durability of concrete.

The change in humidity often causes the deformation of concrete. In order to get the shrinkage strain of concrete, a great number of researches proposed many testing methods to experimentally determine this value. However, due to lack of the knowledge on the mechanism of moisture migration and the shrinkage strain, and the limitation of the technology conditions, the overall shrinkage strain experimentally obtained was tested under a specific laboratory conditions which cannot be universally used by other researches. Furthermore, in this method, the relationship between the age and the shrinkage deformation in concrete is usually obtained by directly connecting or mathematics fitting of the tested data, which only show the macroscopic appearance of concrete shrinkage, not realistic feature at the mesoscipic level being better understood [22]. In order to establish the relationship between the moisture content and shrinkage strain, some researches indicated that it can be assumed that the increment of shrinkage strain ($\Delta\varepsilon_{sh}$) is proportional to the change of humidity (Δh) as the humidity within the range of from 60% to 100% [23–27]. However, other researchers suggested that there is a nonlinear relationship between the change of humidity and the shrinkage strain incremental [28]. In recent years, an increasing number of researches were interested in studying the shrinkage and moisture diffusion at mesoscopic level. Man and Lytton [29] indicated that the magnitude and the shape of the drying-shrinkage curve depends on the compressibility of the ingredients, the amount of aggregate, and the pore structure of the cement, and found that the relationship between drying shrinkage and water potential is a logarithmic curve. Shimomura et al. [30] proposed a micromechanical model for moisture diffusion and the associated shrinkage of concrete, which is based on the micropore structure of concrete and the thermodynamic behavior of the water in the pores. Idiart et al. [31] proposed a hygro-mechanical coupling model at the meso-level to analyze the drying shrinkage in concrete, which was based on the finite element method and used the zerothickness of interface elements equipped with a fracture-based constitutive formulation to represent cracks, explicitly taking into account the influence of (micro) cracks on the diffusion of moisture. Furthermore, the effect of size and volume fractions of the main heterogeneities of concrete on the drying process and drying-induced microcracking are also addressed. Granger et al. [25] proposed a simple experimental method based on micromechanics making use of experimental curves of drying shrinkage as a function of weight loss and allowing the flanking and specification of certain properties of structural drying creep. This model is in satisfactory agreement with the curves of shrinkage as a function of weight loss. In addition, the simulation results are very instructive, as regards with the spacing and the width as well as the depth of cracks which appear in the drying shrinkage and creep tests. Neubauer et al. [32] developed a two-dimensional digital-image-based model of mortar and gave a specific attention to the properties of the interfacial transition zone (ITZ) between cement paste and aggregate. The results showed that Young's modulus of the ITZ is about from one third to one half of the modulus for bulk cement paste and the unrestrained shrinkage of the ITZ material is close to the shrinkage of bulk cement paste when both are averaged over a 20 μm ITZ. Sadouki and van Mier [33] studied the moisture flow in cement composites using the lattice-type approach at the meso-level, and found that the effective transport properties of the composite are functions of geometrical and physical properties of the different phases in the heterogeneous material. In particular, the model has been used to study the effect of the permeability of the interfacial transition zone and the effect of non-saturated porous aggregates on the moisture flow in concrete.

In mesoscale modeling of the moisture diffusion and the shrinkage of concrete, concrete can be considered as a three-phase system made up of coarse aggregate, mortar matrix, and ITZ. For most case, each phase of concrete is thought to be homogeneous material. However, by the influence of microstructure such as