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Computational homogenization for thermal conduction in heterogeneous concrete after mechanical stress

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HIGHLIGHTS

- A meso-scale method to simulate thermal conduction in damaged concrete was built.
- Results obtained with series model is more sensitive to damage than parallel one.
- The ETC of concrete decreases with damage accumulation during the loading process.
- The effect of loading types on thermal conduction depends on their directions.

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ABSTRACT

Concrete structures are subjected to various loadings during their service life and their internal structures will be changed, resulting variations in mechanical and thermo-physical properties. To investigate the effect of mechanical stress on thermal conduction, a computational homogenization method from a mesoscopic perspective was proposed in the present work. In the simulations, concrete was considered as a three-phase composite material consisting of aggregate, mortar matrix and the interfacial transition zones (ITZs) between them. The mechanical analysis was conducted firstly to study the damage distribution within concrete. The outcomes of mechanical computation were then used as the initial input data in the thermal conduction computation. The equivalent thermal conductivity of damaged element was homogenized by a composite mechanical method based on damage and the initial thermal conductivity of sound material. Accordingly, a meso-scale model in which the mechanical and thermal behavior were one-way coupled was built. The method was calibrated by comparing the numerical results with the available experimentally measured ones. Based on the verified simulation method, effective thermal conductivity (ETC) and temperature field of concrete subjected to different loading levels were calculated. Besides, the effects of loading type (compressive and tensile loadings) on ETC and temperature field of concrete were studied. It is found that ETC of concrete decreases with an increasing loading level. In addition, the effect of tensile loading on thermal behavior depends on whether the direction of thermal conduction is parallel or perpendicular to loadings.

1. Introduction

1.1. Background

In the context of energy efficient building design or calculation of temperature profile in fire-exposed structures, massive structures, chemical industry, nuclear reactor structures and fire protection [1,2], thermal conductivity is the property of concrete that plays a key role in all heat transfer calculations [3]. Until now, lots of efforts have been devoted to investigate the thermal conductivity of concrete. Nevertheless, most of them mainly concentrate on the thermal conductivity of concrete at a stress-free state, i.e. without considering the effect of external mechanical loadings. In addition, other material properties of concrete subjected to external loadings, either cracked or not, were also studied far less often than that of the sound concrete. For example, mechanical properties were studied in [4–8], water transport properties and air permeability in [9–14], chloride transport in [15–19].

During its service life, concrete can be subjected to combined effects of mechanical loads, chemical attacks and temperature variations [20,21]. Generally, the service loadings by themselves are not enough to cause a significant degradation to the mechanical

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properties of concrete. However, the structure and distributions of the pores and micro-cracks within concrete may be changed with the time by the applied mechanical stress and even new macro- or micro-cracks may generate into the bulk concrete [20–22]. As a result, the microstructure of concrete is affected in a significant way, which causes changes of all material parameters that should be related to the damage of the original material, including the thermal conductivity [20].

1.2. Review on thermal conduction in concrete subjected to mechanical stress

So far, some studies concentrating on the effect of external loadings on materials' thermal conductivities have been conducted by utilizing experimental methods, theoretical analyses and numerical simulations. In the experimental studies, Černý et al. [23] measured the effect of compressive stress on thermal properties of Portland cement mortar in wide temperature and moisture ranges and found that the thermal conductivity of samples exposed to 90% of compressive strength load was higher than that of the unload samples. This may be awarded to the convective effects which were pronounced due to both temperature and pressure gradients. Perkowski [24] and Vejmelková et al. [20] tested the thermal conductivity of high performance concrete samples in loaded and unloaded states and a decrease of thermal conductivity by 20% and 40% on the average due to damage evolution caused by mechanical loadings were observed, respectively. Zhang et al. [25] measured the thermal conductivity of 6 concrete specimens under uniaxial compression and concluded that thermal conductivities in both directions that parallel and perpendicular to the compression loadings decrease gradually with the increasing load level.

In the theoretical analyses, considering the thermal expansion induced micro-cracks are penny-shaped, Hasselman [26] derived expressions for estimating the effect of cracks on the thermal conductivity of solid material in terms of crack density, size and orientation. Dryden et al. [27] analyzed the axial heat flow within an aligned fiber composite containing matrix cracks bridged by fibers and found that for volume fraction and crack spacing occurred in actual composites, the thermal interaction between cracks can be almost negligible when the fiber/matrix interface is perfect. By applying an explicit effective medium approximation scheme on the basis of a simple micro structure description of the material, Bary [28] predicted the thermal conduction parameters of isotropic micro-cracked hydrated cement pastes in unsaturated conditions. On the basis of the prediction model for the undamaged concrete and the experimental observations, Zhang et al. [25] proposed a mesoscale model for studying thermal conductivity of damaged concrete assuming that damaged concrete was isotropic and damaged phase was served as an insulator.

In the numerical simulations, only finite element approach was applied to investigate the thermal conductivity of concrete subjected to external loadings. Considering the heterogeneity of concrete by the Weibull distribution assumption, Tang et al. [1] presented a two-dimensional numerical model to examine the influences of meso- and macroscopic structure on the effective conductivities of mortar and concrete. The numerical results indicated that the conductivity slowly decreases with damage accumulation. Wu and Wriggers [29] numerically explored the phenomena that the effect of debonding at interfacial transition zone on the thermal conduction by establishing a cohesive zone model characterized by traction-separation law that combined with micromechanically motivated thermal flux-separation relation. In light of that concrete often cracks, representing cracks by equivalent plastic strain, Shen et al. [30] studied thermal conductivity of tensile-cracked concrete with the series model.

The abovementioned studies promote the understandings of thermal conduction within concrete after mechanical stress. However, there are still some problems that remain unsolved. For instance, the experimental results are not consistent with each other quantitatively. The theoretical analyses do not take the real internal structure of concrete into account either. Moreover, the micro-/meso-scale mechanism of the effect of external loadings on thermal conduction behavior in concrete has not been sufficiently studied.

1.3. Scope of the study

As known, a change of internal structure will take place within concrete subjected to external loadings, resulting in a variation of the properties of concrete [13,22,25]. This change is not uniform due to the inherent heterogeneity of concrete at micro-/meso-scale which can influence the thermal conduction behavior in concrete. However, this effect has not been considered in almost all the previous studies. In light of this, as a main contribution, the heterogeneity of concrete meso-scale structure was taken into account and concrete is assumed to be a composite consisting of three phases, i.e., aggregate, mortar matrix and interfacial transition zones (ITZs) between the former two phases. A mesoscopic computational homogenization approach for studying the effect of mechanical stress on thermal conduction behavior within heterogeneous concrete was presented in this paper. The damage distribution of a concrete specimen was achieved firstly by a mechanical analysis in the simulation. The equivalent thermal conductivity of the damaged micro-unit was then homogenized depending on its damage level and thermal conductivities of materials in sound state and this is the other contribution of the present work. In this way thermal conduction behavior in concrete after mechanical stress was investigated.

2. Description of thermal conduction in damaged materials

2.1. Thermal conductivity of damaged materials

As illustrated in Fig. 1(a), concrete is a multi-components composite material containing of the random-distributed aggregate particles and hydraulic cement blinder, and its internal structure is inhomogeneous at meso-scale [31]. After external mechanical loading or other deterioration processes, the inner structure of concrete becomes more discontinuous and heterogeneous due to the occurrence of distributed micro-cracks (referred to as damage hereafter) in mortar or in the interfacial transition zones (ITZs) between the coarse aggregate and surrounding mortar as depicted in Fig. 1(b). This change will result in a variation of concrete's thermos-physical or mechanical properties, herein thermal conductivity.

After mechanical stress, a micro unit of concrete can be regarded as a biphasic material consisting of continuous matrix and cracks (damage). And the volume fraction of the crack phase, denoted as d, can be used equivalently to describe the damage level of a micro-unit. As shown in Fig. 2(a), the damage variable d can take values from zero, representing the undamaged material, to one, which represents a totally damaged state. In the realistic concrete, the cracks are usually filled with air, resulting an insulation of heat due to the low thermal conductivity of air. Obviously in Fig. 2(b), when there is no damage generated in the micro-unit (i.e., $d = 0$), its thermal conductivity equals to that of the original material. While if the micro-unit is totally damaged ($d = 1$), its thermal conductivity is the same as that of air supposing that the damaged (cracked) zones are filled with air. However, when the value of damage factor d is between 0 and 1, both sound and