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Investigation of characteristics and responses of insulating cement paste specimens with Aer solids using X-ray micro-computed tomography

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HIGHLIGHTS

- Aer solids are used for cement paste specimens to enhance the insulating effect.
- Micro-CT and probability functions are used to characterize the void distribution of samples.
- Effect of Aer solids on the material property is examined using experiments and simulations.
- The relationship between the void distribution and the material property is investigated.

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ABSTRACT

Insulating concrete is a type of material designed to enhance energy efficiency by reducing thermal conductivity. It contains numerous voids induced by the use of air-entraining admixtures or aggregates, and these voids strongly affect the characteristics and responses of the material. Thus, appropriate methods to examine the void distribution of materials are needed. Here, X-ray micro-computed tomography (micro-CT) is adopted to investigate the spatial distribution of voids in a material without destroying the specimen. By using micro-CT, a series of cross-sectional images with the micrometer range pixel size can be obtained. Then, void density contour and probabilistic description methods, such as two-point correlation and lineal-path functions, are used to describe the void distribution inside the specimen. In this study, Aer solids, small prefabricated hollow air bubbles, are used for insulating cement paste specimens to increase the insulating effect. The cement paste specimens with different void ratios and Aer solids are generated, and their void distribution characteristics are investigated using the methods mentioned above. The thermal and mechanical responses of the insulating specimens are also evaluated by experiments and numerical methods. The effect of Aer solids on the material characteristics and the relationship between void distribution and material responses are confirmed from the obtained results.

1. Introduction

For several decades, many investigations related to energy efficiency have been performed in various fields to save energy consumption. In the construction material field, many studies have been conducted to develop advanced construction material to reduce energy loss at the material level. Among them, insulating concrete is a type of material designed to reduce heat conduction for saving heat consumption, and many researchers have studied developing advanced insulating materials [1–4]. In general, concrete is a random heterogeneous multi-phase material, and its material characteristics are strongly affected by the spatial distribution of its components. In particular, insulating concrete contains numerous voids owing to the use of air-entraining admixtures or aggregates, and these voids strongly affect the material properties, such as thermal conductivity and strength [5–7]. Thus, appropriate methods are needed to investigate the void distribution inside insulating concrete in a more accurate and efficient manner.

The void or inner structures of cementitious materials have been investigated using various techniques. For example, scanning electron microscopy (SEM) and optical microscopy (OM) have been used to identify the characteristics of material structures [8–10]; however, SEM and OM can only provide information about the specimen surface, and destructive processes, such as polishing

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and drying, are required for preparing the sample. Mercury intrusion porosimetry (MIP) can also be used to investigate the pore size distribution; however, the specimen is damaged during pressure loading, and this method is limited to measuring the open porosity [11,12]. To overcome the limitations, X-ray micro-computed tomography (micro-CT) is used in this study to investigate the spatial distribution of voids inside insulating concrete specimens. Micro-CT is a nondestructive method that uses X-ray to describe the inside of an object without cutting and has been utilized to investigate the characteristics of concrete materials. Chotard et al. [13] used CT images to characterize the early hydration of cement, and Gallucci et al. [14] investigated the microstructure of cement paste using micro-CT. You et al. [15] used CT images to predict the dynamic modulus of asphalt mixture, and Rougelot et al. [16] examined microcracking in cement paste using CT images.

Several studies have also used micro-CT to investigate the material properties related to the void distribution of concrete materials. Lu et al. [17] evaluated the permeability of concrete by investigating the relationship between void connectivity and chloride migration, and Zhang et al. [12] investigated the mass diffusivity of cement paste using micro-CT images. Chung et al. [18] investigated the anisotropy of the void distribution and the stiffness of lightweight aggregates using CT images, and [19] examined the pore forming process in lightweight aggregate using micro-CT. Chung et al. [20,21] also used CT images to investigate the correlation between probabilistic characteristics and permeability of porous concrete. Bossa et al. [22] adopted micro-CT to characterize the pore-network of a leached cement paste, and Zhang and Jivkov [23] investigated the elastic properties and fracture behavior of hydrating cement paste using high-resolution micro-CT images; their results demonstrated that the inner voids within porous materials can be identified using micro-CT images without inflicting any damage to the specimen.

In this study, the effect of void distribution on the material properties of insulating material is examined using micro-CT imaging. For the purpose, cement paste specimens with different void ratios are prepared. To secure the regularly dispersed voids within the specimens, small prefabricated hollow polymetric spheres (Aer solids) are used for insulating cement paste specimens to increase the insulating effect. Then, the spatial distribution of voids and Aer solids is described using micro-CT images. Herein, the use of micro-CT images with micrometer resolution is necessary because the Aer solids have diameters on the order of a few micrometers, and these cannot be visualized effectively from a general CT device.

Qualitative characterization of the void distribution is performed using low-order probability functions and void density contours. Low-order probability functions, such as two-point correlation and lineal-path, are used in this study to describe the spatial distribution of voids including Aer solids. The two-point correlation [24] and the lineal-path [25] functions are used to investigate the degree of void clustering and the void connectivity for a specific direction in the specimen, respectively. The probabilistic characteristics of the specimen can be obtained using these functions with only a small amount of data and can also be utilized to predict the material properties related to the void distribution, such as thermal conductivity, strength, and directional modulus [18,26–28]. The thermal conductivity and strength of the insulating cement paste specimens are evaluated by numerical simulations and experiments. The similarity between numerical and experimental results is verified, and the relationship between the void distribution characteristics and responses is also demonstrated to examine the effect of Aer solids on the material characteristics of the insulating specimens.

2. Insulating cement paste specimens and micro-CT

2.1. Insulating cement paste specimens with Aer solids

Insulating concrete is a widely used structural material to enhance energy efficiency by reducing heat conduction through the material. In general, insulating concrete contains a rigid thermal insulation or void to improve the insulation effect. In particular, the voids within the specimen play an important role in reducing heat conduction; therefore, an appropriate securing of voids within the material is necessary for insulating concrete. Here, small prefabricated hollow plastic air bubbles named 'Aer solids (Sika, Germany)' are added to insulating cement paste specimens for the insulating effect. Aer solids are expected to be more effective for insulation than other admixtures and aggregates due to their uniform shapes and sizes. Therefore, the use of Aer solids can secure regularly dispersed spherical void within the specimen. Aer solids contain spherical voids within the plastic shells, and 90% of them have diameters of 25–60 μm (median diameter: 35 μm). The density of Aer solids is 0.2 g/cm^3, and the void volume ratio is 77%. In this study, cement paste specimens with different sizes and void distributions are prepared, as shown in Fig. 1. The specimen in Fig. 1(a) is a cement paste specimen produced using a thin glass tube with a length and inner diameter of 70 mm and 0.9 mm, which is the optimal size to obtain high-resolution micro-CT images, and the mix design of the specimen is shown in Table 1; the target void ratio from the use of Aer solids is 10.46%, and this sample is used to investigate the spatial distribution of Aer solids within the specimen. However, this specimen size is difficult to use in a real experiment. Thus, a series of cubic cement paste specimens with different amounts of Aer solids are also produced to evaluate the material properties of the specimens, such as thermal conductivity and strength, as shown in Fig. 1(b). The edge length of each cube is 20 mm, and the effect of Aer solids on the material properties of the specimen is examined experimentally using these samples. The mix design of each specimen in Fig. 1(b) is shown in Table 2. In this table, the target void ratios of SB and LB samples from the Aer solids are 12.92% and 25.83%, respectively. All the

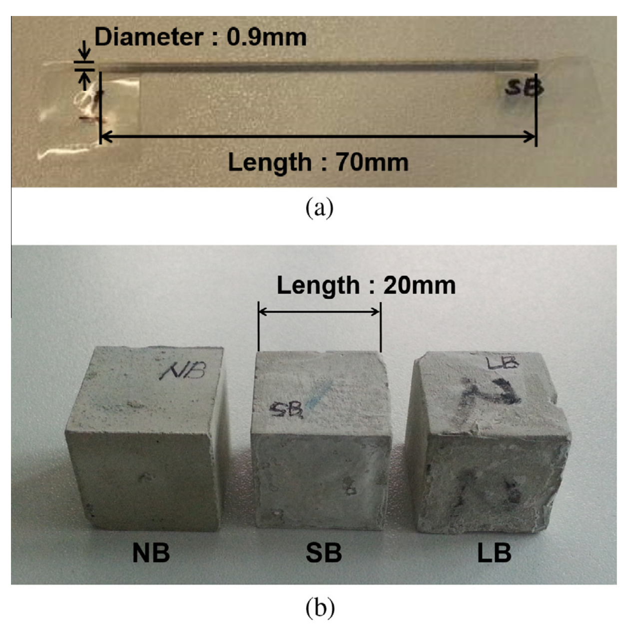

Fig. 1. Insulating cement paste specimens: (a) thin specimen with Aer solids, (b) cubic specimens with/without Aer solids. (Note: In cubic specimens, the NB, SB, and LB denote no bubble, small amount of bubbles, and large amount of bubbles within the specimens, respectively.)