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Development of advanced insulating materials for innovative and sustainable structures

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Abstract

In building and construction material fields, the reduction of energy consumption becomes a key issue, and many efforts are being carried out to increase energy efficiency. In particular, investigation of various types of concrete materials to enhance energy efficiency has been performed during the past decade. The main objective of this study is to develop eco-friendly insulating concrete with recycled aggregate. For this purpose, different types of recycled aggregates obtained from waste concrete are utilized. By examining the characteristics of recycled aggregates and concrete with low density, a high-performance insulating material which can reduce the energy consumption and improve a positive impact on environmental problems can be developed. For more detailed investigation of the characteristics of insulating concrete with different aggregates as well as pore distribution characteristics, micro-computed tomography (micro-CT) image based and probabilistic methods are adopted. The material responses of insulating concrete with different components are complementarily evaluated using experiments as well as numerical simulation tools. From the obtained results, optimize the effective pore size, the pore size distribution as well as its shape for enhancing the insulating and strength performance of the insulating concrete specimen can be identified, and the proposed multi-scale analysis and design methodology ranging micro and macro scales for developing advanced insulating concrete are demonstrated.

Keywords: Insulating materials; recycled materials; multi-scale analysis; pore structures; micro-computed tomography

1. Introduction

Recently, improvements in energy efficiency have become a worldwide issue to limit global CO_2 emissions and energy consumption. In civil and construction engineering fields, energy efficiency has become an important issue, and many efforts are being made to reduce energy consumption as well as to reduce environmental pollution by recycling of construction waste. Among them, many investigations of insulating materials for reducing energy consumption have been performed during the past decade at construction material level. Insulating concrete is a type of material designed to reduce thermal conductivity for saving operational energy. In general, the insulating material contains numerous pores inside the specimen, and lightweight aggregates or air-entraining admixtures are used to secure the pores inside the materials. In particular, the pores and aggregates within insulating materials play an important role in determining the heat conduction and strength of the specimen [1,2].

An insulating concrete is a material designed for reducing heat conduction through entrained pores in the material [3,4]. A specimen of insulating concrete contains numerous pores, the spatial distribution of which strongly affects the physical properties of the material, such as thermal conductivity and strength. The thermal performance of the material improves as the porosity increases while the strength of the material decreases [5,6,7]. Therefore, an appropriate method for examining the pore distribution in the materials is necessary for better understanding of the material behavior.

In this study, the effect of different types of recycled aggregates on the material properties of insulating concrete was investigated. Different types of recycled aggregates from construction demolition waste were utilized for generating a series of eco-friendly insulating concrete specimens. To investigate the inner structure of aggregates and concrete specimens, micro-CT images were utilized as a nondestructive method. In particular, the spatial distributions of the pores and aggregates within each specimen were characterized using probabilistic methods, and the thermal and mechanical properties of the specimens were also evaluated by means of real and numerical experiments in micro- and macro-scales. The obtained results demonstrate an effect of recycled-eco-friendly components on insulating concrete, and the systematic tools in this research can be utilized as a promising approach to develop high-performance insulating materials.

The effect of pore distribution as well as other constituents is investigated by evaluating the material characteristics and responses, and the optimal design process to generate high-performance eco-friendly insulating concrete is proposed. The aims of this study are summarized as follows; first, production of lightweight concrete specimens with crushed and expanded waste glass (WG) aggregates, respectively, by replacing all fine aggregates with WG aggregates; second, application of a grading curve to maximize the volume of the crushed and expanded WG aggregates inside the specimens; third, investigation of the effects of crushed and expanded WG aggregates on pore characteristics (via image-based techniques) and the thermal and mechanical properties of the materials. For these purposes, lightweight concrete specimens that contained only crushed and expanded WG aggregates (100%) as fine aggregates were prepared. In addition, a methodology to examine the spatial distributions of pores, recycled aggregates, and other constituents in insulating concrete is investigated here, and the relationship between the material characteristics (component distribution) and response (thermal and mechanical behaviors) of insulating concrete is also evaluated.

2. Methodologies

In this study, different recycled and expanded aggregates and admixtures were used to generate insulating concrete specimens. In particular, recycled aggregates from construction demolition waste were utilized for insulating concrete. These aggregates were classified by particle sizes and categorized to evaluate the effect of recycled fine aggregates as well as recycled coarse aggregates on the material properties. In addition to the use of recycled aggregates, a recycled crushed glass material was used to insulating concrete materials to consider environmental

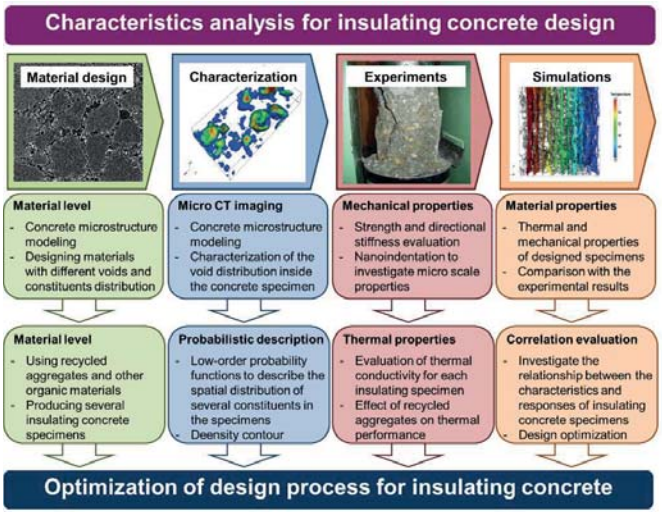

Fig. 1 Procedure for developing insulating concrete

problems, and the material characteristics and properties of these insulating concrete specimens with different mix designs were investigated. In general, porous concrete materials with large porosity such as insulating and lightweight concrete have less strength than other types of concretes. Therefore, a proper investigation of insulating concrete to optimize the pore size and distribution that satisfy the minimum strength criteria as well as the maximum thermal performance is required. Procedures required to develop insulating concrete are presented in Fig. 1.

2.1. Specimen preparation

For insulating concrete, several types of lightweight aggregates and air-entraining admixtures can be used. In particular, recycled aggregates from construction demolition waste are utilized for insulating concrete to reduce the amount of waste. Considering environmental issues, the energy consumption and waste of resources can significantly be reduced by using these recycled or organic materials. However, those proposed insulating concrete materials should have sufficient physical properties, such as strength and thermal conductivity, to be utilized as construction materials. Therefore, appropriate methods to evaluate the characteristics and properties of insulating concrete are required. For the purpose, three different mixes were designed and prepared. The concrete specimens with crushed waste glass, expanded waste glass, and natural sand were denoted as CG, EG, and NS, respectively. The material properties of proposed insulating concrete were evaluated using nondestructive visualization, probabilistic description, and numerical simulation as well as experiments.

2.2. Micro-CT imaging

Computed tomography (CT), a non-invasive method, was used here to investigate the spatial distribution of the constituents and pores of insulating concrete [8, 9]. In this method, a series of cross-sectional images of insulating concrete are generated using X-rays without damaging the specimen. These images are expressed by a pixel, which is a unit for constructing 2D images. A micro-CT imaging process that converts images from an 8-bit image to a binary image was used to examine the specific constituents of insulating concrete. Subsequently, 3D images of the insulating concrete can be generated by stacking the cross-sectional images. For more detailed investigation of the pore distribution within the specimen, mercury intrusion porosimetry (MIP) is also adopted as a complementary tool in CT.

2.3. Probabilistic methods

Probability-based functions were used to describe the spatial distribution of constituents in insulating concrete. Here, the spatial distribution of pores and other components inside the insulating concrete specimen was characterized using probabilistic characterization methods, such as low-order probability functions (two-point correlation, lineal-path, and two-point cluster functions) [10,11,12]. For quantitative description of the pore distribution inside the insulating concrete specimen, low-order probability functions that require only a small amount of data to describe the characteristics of phase distribution can be utilized. As an example of probability functions, two-point correlation, lineal-path, and two-point cluster functions can be used. To describe the density of pores or other constituents in the specimen, pore (or constituent) density contour can also be visualized using CT images. In addition, for the modeling of a sample specimen with a reconstruction method, these probabilistic functions can also be adopted. The relationship between probabilistic characteristics of the pore distribution and the simulation of thermal conductivity as well as the difference between the pore distribution of concrete specimens with and without specific constituents were evaluated to investigate the effect of admixtures on the concrete specimen.

2.4 Property evaluation

The thermal and mechanical properties of concrete materials are strongly affected by the spatial distribution of pores, aggregates, and other constituents. Especially, porous media such as insulating and lightweight concrete have less strength and are more deformable than other types of concretes due to their larger porosity; appropriate and accurate investigation for the strength of insulating concrete material is necessary. For this purpose, material properties such as thermal conductivity and strength of concrete can be examined through experiments and simulations (finite element analysis). To obtain the material responses of concrete materials from a simulation, a commercial finite element (FE) analysis tool, such as ABAQUS, can be utilized. Multi-scale analysis and design methodology in the range of micro-scale can be adopted to investigate the behavior of insulating concrete materials in detail. For more

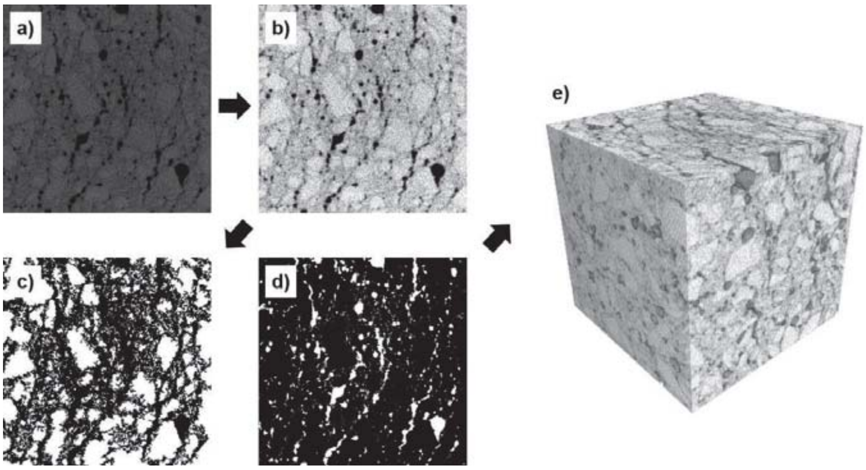

Fig.2 Micro-CT imaging to investigate the pore and solid characteristics: (a) original CT image; (b) contrasted image; (c) binary image for aggregates; (d) binary image for pores; (e) 3D micro-CT image (Note: in (c) and (d), the white regions represent the aggregates (c) and the pores (d), and the black is a background.) [16]

detailed investigation of the material behavior, experiments for evaluating the strength and directional stiffness were also performed, and thermal conductivity values were measured using a HotDisk device, a tool designed to detect thermal properties of materials. The proposed multi-scale analysis framework can be applied to estimate the performance enhancement of insulating concrete such as strength and thermal conductivity with optimized pore size and distribution in the concrete specimen. Using these methods, we can find the relationship between the characteristics and the material properties of insulating concrete materials with different recycled materials and pore distributions and can find their effects on the material characteristics. The results can be used as a base for the improvement of the insulating and strength properties of environmental friendly insulating concrete.

3. Example results

3.1. Crushed glass and expanded aggregates

Here, as an example, crushed glass and other types of lightweight aggregate were used to replace a whole aggregate in the materials. A series of lightweight concrete specimens with recycled crushed glass were produced. Here, lightweight concrete specimens contained only crushed and expanded waste glass as fine aggregates, and their pore and structural characteristics were examined using image-based methods, such as scanning electron microscopy (SEM), X-ray micro-computed tomography (micro-CT), and automated image analysis (RapidAir).

Fig. 2 shows micro-CT imaging of the specimen with crushed glass aggregates. In Fig. 2(a), the original 8-bit -CT image of the sample with crushed glass aggregates is presented. The original image is composed of 800×800 pixels which range from 0 (black) to 255 (white) with a pixel size of 29.7 μm. Median and contrast filters in MATLAB were applied to the original image to enhance the image quality, as shown in Fig. 2(b). To classify specific components such as aggregates and pores, the filtered image was segmented using the multi-thresholding method and the modified watershed algorithm [13]. Fig. 2(c) and (d) are sample binary images of aggregates (crushed glass) and pores, respectively. In each figure, the white regions are aggregates (Fig. 2(c)) and pores (Fig. 2(d)), and black represents the background. A 3D image of the specimen was obtained by subsequent stacking of 2D images (Fig. 2(e)). Using these segmented images, solid and pore characteristics including porosity can be effectively identified.

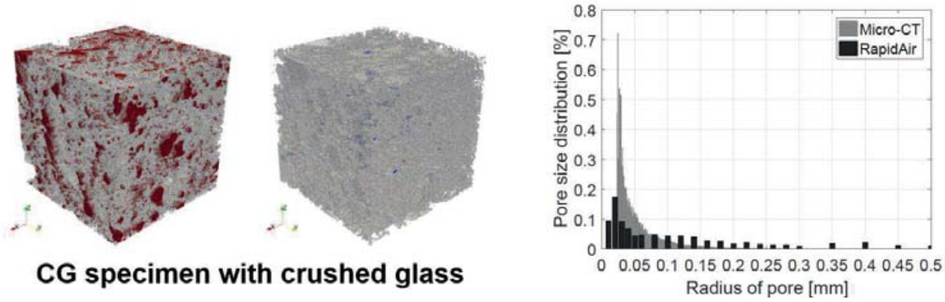

Fig. 3 Pore structures of the specimen with crushed glass (CG) aggregates (left) and its pore size distribution (right) (Note: in the left figure, the 1st figure presents the pores within the solid (matrix) (red), while the 2nd figure presents the pores inside aggregate particles (blue).) [16]

The pore structures of the specimens were also measured using a RapidAir 457, which is an automated-air-void-analyzer (Concrete Experts International, Sweden). The RapidAir 457 consists of a computerized control unit (PC) with a color monitor, video camera, and microscope objective mounted on a moving stage. The result obtained from the RapidAir was compared with the result from micro-CT imaging.

Fig. 3 shows the pore size distributions of the specimens. In all cases, the general trend of the pore size distribution is almost identical, even though the peak values and the distribution of the pores larger than 300 μm are slightly different; the differences are attributable to the heterogeneity of the specimens because the RapidAir is a method based on a 2D image, while the micro-CT is a 3D based method. In this figure, the EG specimen includes more pores than other specimens, and pores >100 μm are dominant in this specimen. Moreover, compared to the NS specimen, the CG specimen mainly contains pores <60 μm, which are affected by the interlocking of crushed glass and can lead to larger mechanical properties as well as the smaller thermal conductivity of the material.

The detailed porosity of the specimens was calculated as shown in Fig. 4. In this figure, the porosity values in each phase of the specimens are presented, and the pore characteristics discussed above are quantitatively confirmed. As shown in the micro-CT images, the porosity of the EG specimen is significantly larger than that of the other specimens; this result being mainly from the highly porous aggregates in the EG specimen. It should also be mentioned that the porosity of natural sand aggregates is slightly larger than that of crushed waste glass aggregates, and this affects the difference between the characteristics of specimens with each aggregate [14,15].

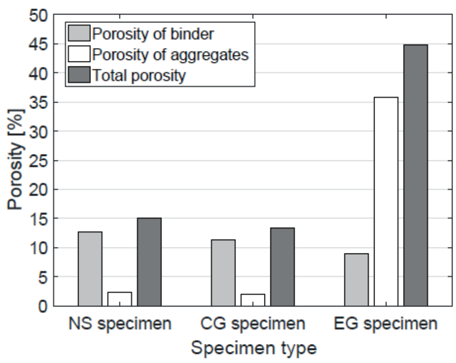

Fig. 4 Porosity data of each phase in the specimens (Note: the total porosity values of each case are 15.1%, 13.4%, and 44.8% for NS, CG, and EG specimens, respectively.) [16]

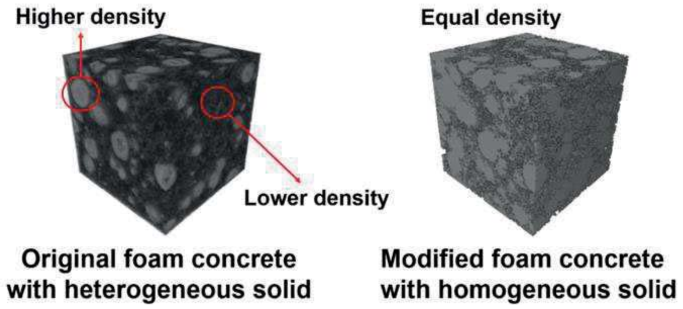

Fig. 5 Original foamed specimen with heterogeneity and modified foamed concrete with homogeneous solid

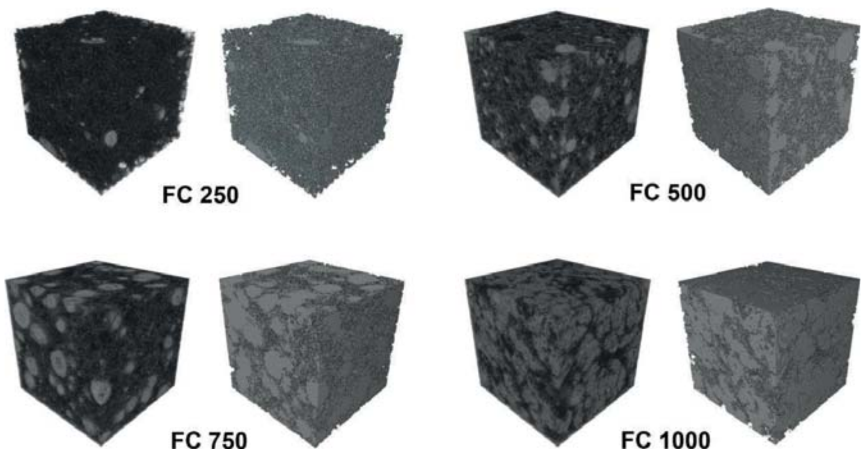

Fig. 6 Micro-CT images of the foamed specimens with different densities (Note: in each case, the left figure is an original 8-bit image, and the right figure represents the solid part of the specimen.)

3.2. Foamed concrete

As another example, micro-CT imaging and numerical approaches can be applied for foamed concrete. Fig. 5 shows the example of foamed concrete. In the left figure, a 3D micro-CT image of the sample foamed concrete is presented. In this figure, it can be seen that solid structure of the specimen is totally inhomogeneous. Fig. 6 shows the examples of foamed concrete specimens with different densities. To figure out the effect of solid density distribution on the material properties, we are going to generate a set of virtual samples with different densities based on the original X-ray micro-CT image and measure its material properties as well as fracture mechanism using numerical simulation tools.

3.3. Property evaluations using experiments and simulations

To investigate the effect of different aggregates and densities, three types of expanded aggregates, such as expanded glass (Liaver®), expanded clay (Liapor®), and expanded foamed glass (Ecoglas®) were used. The lightweight aggregate concrete (LWAC) specimens with Liaver, Liapor and Ecoglas are denoted as LV, LP and EG, respectively, and the numbers denote the density of the specimen (600 and 800 kg/m^3).

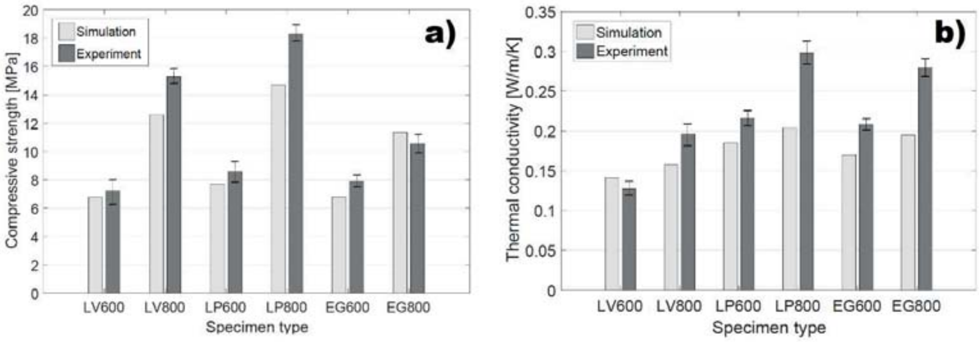

Fig. 7 Material properties of LWAC specimens: (a) compressive strength, (b) thermal conductivity

The compressive strength of the real LWAC specimens was measured using a loading tool, and the simulation was performed using the virtual specimens and the ABAQUS software incorporating the concrete damaged plasticity (CDP) model. The compressive strength results obtained from both experimental and numerical approaches are shown in Fig. 7(a). In this figure, the quantitative differences between experiments and simulations are less than 13% in most cases, which is in reasonable agreement with the experimental results and sufficient to compare the relative magnitude of the compressive strength; the differences are mainly due to the heterogeneity of the aggregate shape as well as its porosity. LV specimens have less compressive strength than LP and EG specimens in each density class.

In addition to the compressive strength, the thermal conductivity of the LWAC specimens was evaluated and compared. The thermal conductivity values of the specimens were evaluated using the transient sensor method as well as FE analysis for both experimental and numerical results. The thermal conductivity of the LWAC specimens is presented in Fig. 7(b). The results from both experimental and numerical approaches are within a reasonable range giving sufficient reason to investigate the relative trend of thermal conductivity, although relatively large differences can be found in LP800 and EG800, both of which include larger aggregate particles.

4. Conclusions

In this study, lightweight concrete specimens with different sources of aggregate were produced and investigated. In particular, as an example of the use of eco-friendly materials, the effect of recycled crushed waste glass and expanded aggregates on concrete was examined according to several investigative approaches. To produce lightweight concrete specimens, crushed waste glass, natural sand, and expanded materials were adopted. Aggregate grading was also considered in maximizing the aggregate content. Pore and solid characteristics of specimens were evaluated using micro-CT, and RapidAir, which is an automated image analysis tool. The compressive strengths of the materials were measured using sensitive experimental devices, and the thermal conductivity was also evaluated using the Hot Disk and the ISOMET in order to enhance accuracy. The concluding remarks of this paper can be summarized as follows:

- Lightweight concrete with density less than 2000 kg/m^3 can be produced by using different aggregates from different source materials. For example, specimens using crushed waste glass show a compressive strength above 36 (MPa) and a thermal conductivity less than 0.6 (W/m/K). Other specimens also showed relatively lower thermal conductivity and higher compressive strength than those of conventional lightweight concrete; the material produced here can be considered an effective lightweight concrete which satisfies both mechanical and thermal properties.
- The image-based methods adopted here, such as SEM and micro-CT imaging, were effectively utilized to investigate the microstructures of the specimens from different perspectives. Particle shape and the intersection between binder and aggregate can be examined using SEM, and pore characteristics, such as the porosity of each component and the pore size, can be nondestructively evaluated using μ-CT.
- When a material contains dense aggregates, such as crushed glass and natural sand, the porosity of the specimen is mainly determined by the binder phase. However, for a material with porous aggregates, e.g., expanded glass,

the porosity of the aggregates is the dominant factor regulating material properties.

In addition to the work reported in this paper, more parametric studies with different mix proportions using crushed waste glass are required to clarify the effects of recycled material on concrete properties. Furthermore, based on the systematic tool introduced here, advanced insulating concrete considering environmental impact can be effectively designed and produced.

Acknowledgements

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