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Analysis of Correlation between the Void Distribution and the Mechanical Property of Lightweight Aggregates

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ABSTRACT

The spatial distribution of voids in concrete affects the mechanical property of materials significantly. Therefore, effective identification of the spatial distribution of voids is important to understand characteristics of concrete. To describe the void distribution inside lightweight aggregate, a computed tomography (CT) image method, which is non-destructive method, is adopted. The spatial distribution of voids of lightweight aggregate along a particular direction is represented by the two-point correlation function. The characteristics of the void distributions are visualized on a sphere and the correlation between the void ratio and anisotropy ratio of the void distribution is examined. Stiffness of lightweight aggregate is also evaluated using finite element analysis. From the result, it is confirmed that direction-based probability distribution function and stiffness using CT images are effective in characterizing void distributions of lightweight aggregates. It is also identified that anisotropy ratio of the stiffness is more affected by the void ratio than anisotropy of the void distribution.

1. INTRODUCTION

Concrete is a random heterogeneous multi-phase material with its material properties being significantly affected by the volume ratio and spatial distribution of concrete constituents, e.g., cement, aggregate, voids, etc. Especially, the void distribution inside concrete strongly affects the strength of concrete. Among several types of concrete, a lightweight concrete is produced to reduce the weight of concrete, and a lightweight aggregate is the main determinant of the properties of lightweight concrete. The lightweight aggregate contains a large number of voids inside the

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material. Therefore, a proper method to investigate the void distribution is needed to understand the characteristics of the lightweight aggregate.

The lightweight aggregate has a high void ratio compared to other aggregates, but it is difficult to identify the void distribution inside the lightweight aggregate without destruction. In this research, computed tomography (CT) is used to investigate the spatial void distribution in a lightweight aggregate.

To characterize the spatial distribution of voids in a lightweight aggregate, the probability distribution function is utilized in this research. The two-point correlation function is used to investigate the void distribution of the lightweight aggregate. In particular, the two-point correlation function for all radial directions in 3D space is adopted to characterize the anisotropy of the lightweight aggregate. With this correlation function, the spatial distribution of voids is expressed as a 3D sphere so that the anisotropy of the void distribution along a specific direction can be identified.

In this research, the anisotropy of the void distribution and the stiffness of lightweight aggregates with different shape and void distributions are investigated. Using CT image processing and the two-point correlation function, the spatial distribution of voids inside the lightweight aggregate is examined. Additionally, the stiffness of lightweight aggregates is calculated using a finite element method. The anisotropy of the void distribution and the stiffness from a set of aggregates are compared to investigate the relationship between the probabilistic characteristics and mechanical properties of the lightweight aggregate.

2. THE VOID DISTRIBUTION OF LIGHTWEIGHT AGGREGATES

In general, investigation of voids inside lightweight aggregates without damaging the specimen is difficult. By utilizing CT images, the void distribution of the lightweight aggregate can be identified. To describe the voids inside the lightweight aggregate, a binary image generated from the 8-bit cross-sectional image is used by image processing with thresholding method (Chung 2013).

To describe the void distribution in a lightweight aggregate, a proper method for characterizing the void distribution is needed. In this research, the two-point correlation function, a low-order probability distribution function that requires a relatively small amount of information is used to characterize the void distribution inside lightweight aggregates (Gokhale 2005, Chung 2013). The two-point correlation function, $P_{ij}(r,\theta,\phi)$ represents the probability that any two points are located in the *i*-phase and *j*-phase. *r* is the distance between two points, θ is the angle between a test line and the *z*-axis, and ϕ is the angle between the projection of a test line on the *xy*-plane and the *x*-axis (Gokhale 2005).

$$P_{ij}(r,\theta,\phi) = f_i f_j [1 - \exp\{-([P_L(\theta,\phi)]_{ij} / (2 f_i f_j))r\}] \quad (i \neq j) \tag{1}$$

The probability that both end points are located in the void phase can be expressed as P_{vv}. To describe the two-point correlation function as a scalar index to visualize on

3D space, P_{vv} is integrated from 0 to 1 for a particular direction and normalized by dividing the void volume fraction within the lightweight aggregate, as shown in Eq. (1). In this paper, the calculation that divides integration of P_{vv} by the volume fraction, is expressed as $\bar{P}_{vv}$:

$$\bar{P}_{vv} = \frac{1}{f_i}\int_0^1 P_{vv} d\bar{r} \tag{1}$$

where *r* is *r/D*, and *D* is the length of the specimen. $\bar{P}_{vv}$ for a direction is then calculated using Eq. (1), and the value is assigned to a point of a grid represented on a sphere. The same procedure is repeated for a number of different discrete directions, and the result is shown as figure. 1. From figure 1, anisotropy of degree of clustering information of the void distribution can be identified.

3. STIFFNESS ANISOTROPY OF LIGHTWEIGHT AGGREGATES

The stiffness of a lightweight aggregate is obtained using the finite element mesh generated from the CT image. In this research, the directional elastic modulus is visualized to describe the anisotropy of the stiffness. The directional elastic modulus is the elastic modulus when an uniaxial load is applied along ***n*** and is defined as:

$$\frac{1}{E(n)} = n_i n_j n_k n_l S_{ijkl} \tag{2}$$

where subscripts *i, j, k,* and *l* are the indices 1, 2, or 3, and S_{ijkl} is the compliance tensor that is related to the stiffness tensor by $S_{ijkl} = C^{-1}_{ijkl}$. The visualization method for the directional elastic modulus $E(n)$ is the same as that of P_{vv} . Analysis of the correlation between the void distribution and directional stiffness of the lightweight aggregates is given in the next section.

4. EVALUATION THE RELATIONSHIP BETWEEN CHARACTERISTICS AND THE STIFFNESS OF LIGHTWEIGHT AGGREGATES

Using the index $\bar{P}_{vv}$, the spatial distribution of voids can be effectively described. and the correlation between the void ratio and anisotropy ratio of the void distribution is examined. The overall stiffness as well as directional stiffness of lightweight aggregates are investigated using finite element method. The relationship between the void ratio and anisotropy of the void distribution and stiffness is shown in figure 1. In the figure, the anisotropy of the stiffness is significantly affected by the anisotropy ratio of the void distribution as the void ratio increases. This trend supports the analysis of the correlation between the anisotropy of the void distribution and the stiffness as well as the void ratio. From the result, it is concluded that the anisotropy of the void distribution affects the anisotropy of the stiffness as the void ratio increases.

5. CONCLUSION

The spatial distribution of voids in lightweight aggregates was examined without damaging

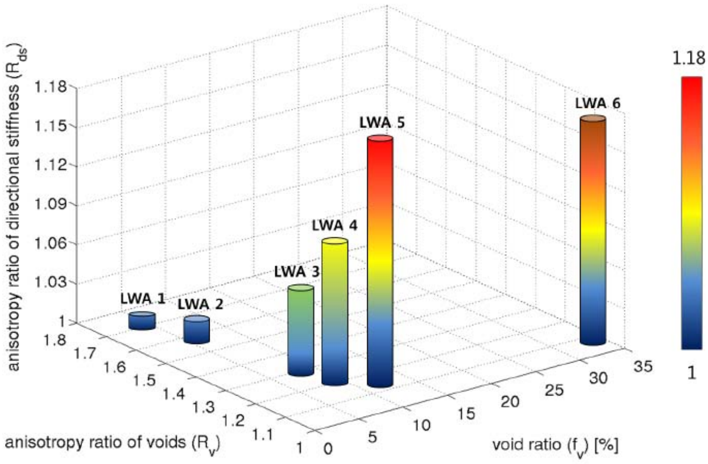

Fig. 1. Correlation between the void ratio, anisotropy ratio of voids, and anisotropy of directional stiffness (Note: R_v=max $\bar{P}_{vv}$ /min $\bar{P}_{vv}$, R_{ds} =max(directional stiffness)/min(directional stiffness))

them using CT images. A two-point correlation function, which is a probability distribution function, was utilized to characterize the void distributions. Lightweight aggregates with different void ratios were used to identify relationship between the void ratio and anisotropy of the void distribution. From these results, it is demonstrated that CT image processing with the probability distribution function and finite element method can be used to analyze the relationship between the characteristics of the void distribution and the mechanical properties of a lightweight aggregate.

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