Evaluation of air void parameters for hardened concrete paste using 3D X-ray CT images

Kwang Yeom Kim¹), Dong Hun Kang²), Tae Sup Yun³)

¹) Korea Institute of Construction Technology, Goyang 411-712, Korea
²) Department of Civil and Environmental Engineering, Yonsei University, Seoul 120-749, Korea
³) Department of Civil and Environmental Engineering, Yonsei University, Seoul 120-749, Korea, taesup@yonsei.ac.kr

ABSTRACT

The air void parameters such as air content and spacing factor are critical to assess the frost-susceptibility of cement-based materials. The addition of air-entraining admixture (AEAs) facilitate the formation of well distributed air voids in matrix whereas the evaluation of air void parameters still follows old-fashioned, yet practically applicable method in two-dimensional space. We implement the 3D characterization method to obtain a spacing factor with 2D and 3D linear traverse methods designated in ASTM C457. The spacing factors for three specimens with different amount of AEAs are compared with values estimated by the statistical method. The statistical approach allows obtaining the unique distribution of equivalent air void diameter and paste-void proximity. Gathered results are compared to assess the evaluation techniques.

1. INTRODUCTION

The spatial configuration of air voids within the cement-based materials strongly influences the mechanical responses of materials when subjected to the thermal and mechanical loadings. In particular, the accurate determination of spacing factor is critical to evaluate the freeze-thaw durability of the materials. The widely used and applicable method often follows the ASTM C457 which is based on stereological examination of two-dimensional (2D) surface sections to gain an understanding of 3D feature of air void systems (ASTM C457). The polished 2D sliced image is prepared and optically examined to obtain the number and length of air voids across the

¹) Senior Researcher
²) Graduate Student
³) Assistant Professor (corresponding author)
traversed line. Despite the inherent lack of 3D features of air voids, this method is time-consuming and tedious job. Other available methods enable more efficient and objective determination of parameters whereas the heterogeneity of air void distribution is hardly captured with the lack of representativeness. Revisiting the concept of spacing factor suggested by Powers (1949), the spacing factor often represents some distance of past-void spacing of an idealized air-void system. However, the paste-air void distance should have a certain form of distribution rather than being expressed as a single value. The numerically simulated air-void system does not correspond to any of alternative spacing equations.

The internal structure of cement-based materials can be obtained by 3D x-ray computed tomography which has been widely used to qualitatively evaluate air void content. Taking advantages of CT imaging technique applicable to the characterization of air void system, we implement the methodology designated in the ASTM C457 (2010) and Powers (1949) as well as the statistical approaches based on the previously reported relationship between 95th percentile of CDF for paste-void spacing and spacing factor (Snyder, 1998).

2. MATERIALS and CT IMAGES

2.1 Specimens
Three cement past specimens are subjected to X-ray CT imaging. Specimens are prepared by mixing 510 g of cement, 247.4 g of water, and 1250 g of find sand. Among three, air-entrained agent (AEA) with 3% and 8% of the cement weight is added (e.g., Non-AE, AE-1 and AE-2 specimens). It is noted that the specimens do not include coarse aggregate to accommodate the limitation of resolution in CT images. Adding the AEA should facilitate the formation or uniformly distributed air voids within the specimen. Each specimen is first subjected to the conventional and optical examination to assess the air void parameters by the ASTM procedure.

2.2 X-ray CT devices
The X-ray CT images are obtained using X-EYE CT scan (SEC corporation, Korea) with a microfocus X-ray tube. The applied voltage and current are 150 kV and 100 µA. The CCD camera collects the x-ray attenuation information upon irradiation as a flat panel detector. The wobbling of the manipulator is controlled within 5 µm allowance. Each pixel has 0.0108 × 0.0108 mm with 1024 × 1024 image size for each sliced image. The interval between images is 0.00868 mm.

2.3 Image Processing
The original X-ray image contains unexpected noises such as beam-hardening and ring artifact so that the series of image enhancement techniques is applied. First, the image is transformed to the Polar Coordinate which makes the radially existing noises straightforward. Then, the 2D Fourier transformation in conjunction with low-frequency filter successfully removes the noises as shown in Fig. 1a. To segment the air voids, the Otsu’s method (Otsu, 1979) is adopted for each image to determine the threshold value by which air void and solid phase are differentiated. The 3D air void configuration of AE-2 specimen after stacking 2D sliced images, for instance, is shown in Fig. 1b.
3. EVALUATION OF AIR VOID PARAMETERS

We explore three different methods to characterize the air void parameter (e.g., spacing factor). As the 2D sliced image by x-ray CT is equivalent to the 2D polished section for the ASTM procedure, the linear traverse method is directly applied to the number of 2D sliced image. The origin of linear traverse method is based on the equivalently spaced air void proposed by Powers (1949) whereas the 2D stereological method is not doable without internal configuration of air voids. Thus, the idealized 3D air void system is reconstructed with the 3D air void information (e.g., total volume and the number of air void object) to directly apply Powers’ concept. Finally, the statistical implementation is made following Synder (1998) to assess paste-void spacing.

3.1 Linear Traverse Method

The image section under investigation has a size of $491 \times 491$ pixels (5.3 mm × 5.3 mm). Total 1024 sliced images are stacked to construct 3D air void system and the arbitrarily orientated traverse lines are drawn. Then, the total number and volume of air voids intersecting all the selected traverse line of a specimen enables calculating the spacing factors (refer to Yun et.al., Kim et.al., 2012 for detailed procedure). Fig. 2a illustrates the schematic concept of linear traverse line method applied in this study. As the number of traverse lines increases, the sampling effect should decreases and the realization eventually satisfies the minimum length of traverse line designated in the ASTM C457. Fig. 2b presents the result of AE-2 specimen highlighting that computed spacing factor converges to the asymptotic value with less variation with increasing total traversed length.
3.2 Equivalently Spaced 3D Air Void Method

Once the 3D air voids are constructed, it is possible to obtain the total number of air
void object and the total volume of air void within a given domain. Then, the
equivalently spaced air void whose size is identical can be distributed and the distance
between diagonally located air void is obtainable, which becomes the spacing factor.
Note again that this concept is reflected to the ASTM C457 that is applicable to 2D
space (Fig. 3)

Fig. 3 (a) Spacing factor defined by the nearest distance between two air void in
diagonal direction (b) 2D air void intersection by traverse line.

3.3 Statistical Method

This distance between the randomly selected paste pixel and the nearest air void
surface defines the paste-void spacing. As the number of selected point increases, the
representativeness should increase. We simulate 10,000 paste pixel and obtain the
distribution of paste-void spacing as shown in Fig. 4. Following the previous study by
Snyder (1998), the value corresponding to 95th percentile of cumulative distribution
function is equivalent to the spacing factor. Total 20 realizations are repeated to obtain acceptable values for each specimen.

Fig. 4 Statistical evaluation of paste-void spacing. 95th percentile value is equivalent to the spacing factor.

The spacing factor values estimated by three different methods are compared in Fig. 5. Values computed by traverse methods are close to each other whereas those are highly overestimated with respect to values by cumulative distribution function. Acknowledging that the paste-void spacing is intuitively close to define the distance between paste and air void, the conventional methods should be carefully calibrated. Furthermore, the investigation of spacing factor based on 3D X-ray CT imaging integrated with the statistical approach is effective in time and cost and provides reliable results.

Fig. 5 Comparison of spacing factors by different methods.
4. CONCLUSIONS

This study shows the feasibility of 3D X-ray computed tomography applicable to characterize the air void system in cement-based materials. The most advantageous function of X-ray CT is the visualization of internal structure which is hardly quantifiable in most engineering practice. The conventional method to evaluating the spacing factor has been continuously proposed in 2D although the spacing factor is truly 3D measure. With the consideration of the significance of spacing factor to assess freeze-thaw durability, it is critical to correctly estimate it. Based on this study, it is concluded that the currently applied methods (e.g., linear traverse method) tend to overestimate the spacing factor compared with the statistically obtained paste-void spacing. It is also noted that the limitation of CT imaging resides in the specimen size because the void size that should be identified for spacing factor is less than 100 µm. Nevertheless, the characterization of construction materials using CT imaging still seems promising.

REFERENCES