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FINITE ELEMENT ANALYSIS OF CONCRETE USING COMPLEMENTARY X-RAY AND NEUTRON COMPUTED TOMOGRAPHY IMAGES

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Abstract: Concrete microstructure plays an important role in the performance and mechanical behaviors of cementitious materials. In the present study, three cases of concrete microstructure are reconstructed based on the information from X-ray computed tomography (CT), neutron CT, and the complementarity of X-ray and neutron CT images. Then, each phase in concrete such as aggregates, voids, and paste were obtained using the Otsu thresholding method. One notices that the X-ray CT is sensitive to the density of materials while the neutron CT is sensitive to the hydrogenous components. Thus, the microstructures obtained from each tomogram is quite different because of the difference in the attenuation coefficient. As a result, the corresponding mechanical properties may change according to the CT images. Then, the finite element analysis is performed for the three cases, i.e., X-ray CT, neutron CT, and complementarity CT. The computational results are compared to demonstrate the effect of the microstructure on macroscopic elastic modulus. The findings of this study shed light on the importance of accurate microstructure representation on the mechanical property of concrete.

1 INTRODUCTION

Concrete microstructure characterization is a vital aspect of studying the performance of concrete materials, including their mechanical strength and durability. At the microstructural level, concrete can be seen as a three-phase material comprising voids, aggregates, and cement paste. The volume, size, and distribution of each phase significantly influence the mechanical behavior of concrete [1], [2].

Various image-based techniques are available for microstructure characterization. In the 2D domain, optical microscopy is used to analyze air content and air void characteristics in hardened concrete through microscopic examination of polished sections. Additionally, an improved 2D image obtained through Scanning Electron Microscopy (SEM) allows for quantifying capillary porosity. However, these 2D approaches are limited to planar section analysis, even though stereology permits a quantitative description of 3D objects observed from 2D images. Unfortunately, the estimated 3D description lacks information about the internal microstructure. Fortunately, recent advancements in non-destructive 3D imaging, such as X-ray and neutron tomography (NT), enable 3D characterization.

Despite these advancements, identifying each phase using a single tomogram (X-ray or NT) remains challenging, particularly due to polymineral aggregates. Progress has been made by combining complementary information from both techniques. By using the complementary images, finite element analysis of 2D sections was possible along the vertical direction of a specimen. This study aims to quantitatively describe the concrete's macroscopic elastic modulus using the complementary CT and neutron images. Additionally, the macroscopic elastic modulus of each single tomogram is evaluated to highlight the challenges of relying solely on either X-ray or neutron images.

The present paper is organized as follow. Section 2 describes the methodology of micro-CT imaging and image processing, while Section 3 presents the finite element analysis of macroscopic elastic modulus evaluation using the X-ray CT, neutron CT, and complementary CT images. Finally, the conclusion of the present image-based analysis is presented in Section 4.

2 METHODOLOGY

2.1 Micro CT imaging

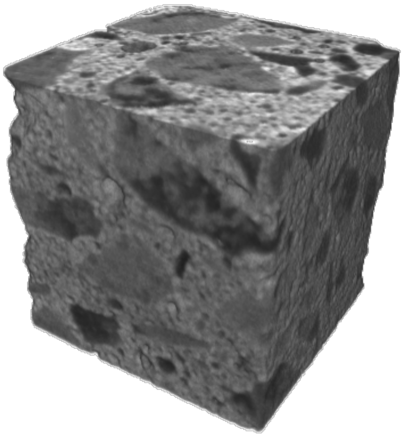
Stack of 2D images were obtained using X-ray and neutron tomography for concrete specimen. Tomography imaging is a process to direct X-ray or neutron at an object from multiple orientations and measuring the intensity decrease. X-ray tomography images were taken at the Korean Institute of Civil Engineering and Building Technology [3]. To obtain the images, source of voltage and energy was respectively 120 keV and 180 uA. The sample was placed 69.5 mm from the source and 916.5 mm from the detector. Image produced had a pixel size of 13.8μm.

For the thermal neutron tomography, images were taken at the RAD facility of the Center for Energy Research in Hungary, using cone beam projection [4]. The distance between the source and the object was 4935 mm, with a distance between the detector and object of 35 mm. The obtained images had pixels size of 43.0 μm.

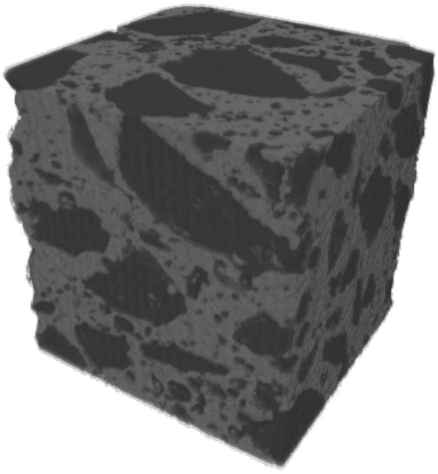
During the 3D reconstruction, a cube forms one voxel with an edge of 13.8μm and 43.0 μm for the X-ray and neutron tomography respectively. The reconstructed volume height is 80.04 mm, which is similar to the physical specimen of 80 mm height.

In order to obtain the complementary X-ray and neutron CT images, both images are combined using a feature-based registration process. Because of the different image resolution and orientation, the neutron CT images are scaled and aligned for each slice to match the X-ray CT images. Then, the information contents of these two images are merged to reconstruct microstructure. Each reconstructed concrete microstructure is shown in Figure 1 (a), (b) and (c) for the X-ray CT, neutron CT and complementary X-ray and neutron CT, respectively.

(a)



(b)

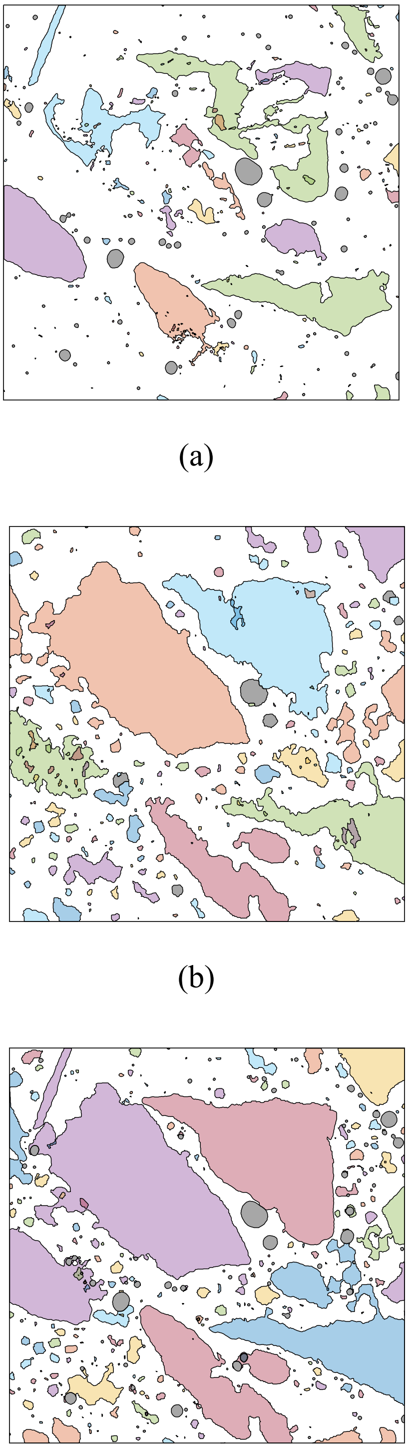


(c)

Figure 1. Concrete 3D reconstruction using (a) X-ray CT, (b) neutron CT and (c) complementary X-ray and neutron CT.

2.2 Complementary image processing

Based on the CT images for a given height of the specimen, three phases of concrete (void, aggregate, and cement paste) are segmented using the Otsu method [5]. The median filtering is employed to reduce signal noises in neutron tomography. The image segmentation results of X-ray and neutron images are shown in Figure 2(a) and (b), respectively. The reconstructed concrete microstructure is quite different from real concrete microstructure if either X-ray or neutron CT image is utilized. Resulting image using the complementarity of X-ray and neutron CT images is shown in Figure 2 (c) to reconstruct concrete microstructure further accurately.



(a)

(b)

(c)

Figure 1. Segmented microstructure using (a) X-ray CT, (b) neutron CT and (c) complementary X-ray and neutron CT.

3 FINITE ELEMENT ANALYSIS

3.1 Test configuration

In a uniaxial tension test, a concrete microstructure is examined within a rectangular domain. The dimensions of this domain are 16.56 mm × 16.56 mm (1,200 pixels × 1,200 pixels). During the test, a uniform displacement of 1.656 μm is applied along the normal to the right edge of the domain. This displacement results in an average macroscopic strain of 0.0001 along the horizontal direction under the plane stress condition. For the materials used in the test, the elastic modulus of the aggregate is assumed to be 60 GPa, while the elastic modulus of the paste is assumed to be 20 GPa. The Poisson's ratio for the aggregate is taken as 0.25, and for the paste, it is considered to be 0.2.

For the image-based analysis, the domain of concrete microstructure is discretized using triangular elements. The microstructure mesh is created from the segmented CT image then the material properties are assigned to each corresponding phase in order to perform a finite element analysis with heterogeneous material. Alternatively, one can utilize an image-based virtual element method (VEM) to accurately and efficiently handle complex concrete microstructure [6].

3.2 Computational results

For each case of the obtained CT images, the volume fraction of each phase of the aggregate, void and cement paste was evaluated and summarized in Table 1. The aggregate volume fractions of the X-ray and neutron CT cases are 21.148% and 43.846%, respectively, they are significantly lower than the volume fraction of the combined CT case (49.876%).

As a result, the computed elastic modulus for the X-ray CT case (23.881 GPa) is lower than that for the neutron CT case (28.395 GPa) due to the different aggregate volume fractions. Each tomogram alone shows a lower elastic modulus compared to the complementary X-ray and neutron CT which is 29.081 GPa.

Table 1. Calculated mixing proportion

	X-ray CT (%)	Neutron CT (%)	Complementary X-ray and neutron CT (%)
Aggregate	21.148	43.846	49.875
Voids	1.685	0.645	1.715
Paste	77.167	55.509	48.409

4 CONCLUSION

The investigation of concrete microstructure involves the segmentation of X-ray and neutron tomography images, capitalizing on the complementary characteristics of their contrast mechanisms. The findings indicate that neither tomogram alone adequately describes the concrete microstructure in this study. However, when the information from both modalities is combined, a successful reconstruction of the concrete microstructure is achieved. Moreover, the macroscopic elastic modulus is evaluated based on the segmented images. The results further reveal that the elastic modulus of the reconstructed microstructure from either X-ray CT or neutron CT exhibits a lower value compared to the microstructure obtained from the complementary images. This underscores the importance of utilizing the complementarity of X-ray and neutron CT in the concrete microstructure reconstruction process.

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