Pore structure characterization of concrete mixtures with different aggregates using digital image processing and analysis

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Abstract. The presence of pores in a volume of concrete obviously affects the compressive strength of concrete (fc). Furthermore, characteristics of pores formed in concrete may vary, such as in shape, in size, in volume, and/or in its orientation tendencies. These characteristics also depend on the ingredient materials and the concrete casting process. In this research, three types of concrete in a form of cylindrical sample were analysed in order to investigate their pore structure characteristics. The first type of specimen is a core sample taken from a beam of an existing reinforced concrete structure building. It has 18 MPa of compressive strength. For the second type, an instant concrete with 40 MPa of designed compressive strength and 9 cm of slump test was chosen. The third sample is a concrete with Oil Palm Shell (OPS) as coarse aggregate substitution with 17 MPa of compressive strength. These three kinds of sample were scanned with a Bruker Micro-CT SkyScan 1173 device. The scanning process produced a set of projection images which were then reconstructed to obtain three-dimensional digital grayscale images. The pores inside the concrete sample are detected as dark pixels, which represent low-density structure. Based on the detected pores, the characteristics such as the volume distribution, the size distribution, the spatial distribution, as well as several structural descriptors such as shape, orientation and eccentricity of the pores were analysed. This study concludes that the type of aggregate greatly influences the characteristics of the pore formed in a concrete.

1. Introduction
Non-destructive characterization of various kinds of porous materials by means of digital image processing and analysis technique has been widely used since the improvement of the digitizing instruments. A simple digital photography for example, can be applied to analyse various characteristics of soil and rock [1-4]. Digital imaging in general has been widely used for rocks characterization, which also well known as digital rock physics [5-8]. The X-Ray Micro Tomography Scan (μ-CT) is one of the intensively used instrument in digitizing the structure of porous materials. In the field of building materials researches, the μ-CT has been utilized for investigating self-sealing in concrete materials [9],
porosity and characterization of building stones microstructure [10], and investigation of water repellent and consolidate in natural building stones [11]. A preliminary study has been previously conducted to show the procedure of imaging technique using µ-CT for concrete samples [12].

This study is aimed to demonstrate the ability of µ-CT to analyse pore structure characteristics of concrete mixtures with different aggregates. Procedure of obtaining digital images using the Bruker SkyScan 1173 High Energy X-Ray µ-CT, the qualitative and quantitative analysis of the pore structure are discussed to reveal the capability this imaging technique.

2. Methods
In this study, three types of concrete specimen in a form of cylindrical sample were analysed to investigate their pore structure characteristics (see Fig 1.a-f). The first specimen is a core sample taken from a beam of an existing reinforced concrete structure building in Jakarta, named sample B1. It has 18 MPa of compressive strength. The second sample is an instant concrete with 40 MPa of designed compressive strength and 9 cm of slump test was chosen, named sample B2. The third sample is a concrete with Oi-Palm Shell (OPS) as coarse aggregate substitution with 17 MPa of compressive strength, named sample B3. Sample B1 consists of common rough aggregate which is made of natural rocks, which are very strong and have irregular shape. This irregular shape of the aggregate forms a good effect on the aggregate interlock mechanism due to its random shape. Sample B2 consists of more fine-grained material such as silica fume and fly ash, which have the size similar to cement particles. For sample B3, OPS aggregate is lightweight material but sufficiently tough. It is natural (so-called BioSource material).

The samples were scanned using Bruker SkyScan 1173 High Energy Micro Computed Tomography scanning system (Figure 1.g.). In this study, the sample was scanned using three different sets of parameters. However, the image pixel resolution of each sample was selected to have the same value, i.e. ~120 µm/pixel. Sample parameters as well as the scanning parameters are listed in Table 1. To generate images with a good contrast ratio of the components and the high signal to noise ratio, different scanning parameters were applied to each of the samples due to their different characteristics.

Table 1. Sample characteristics and scanning parameters for all the three samples.

| Sample Parameters | B1       | B2       | B3       |
|-------------------|----------|----------|----------|
| Height [mm]       | ~60      | ~200     | ~140     |
| Diameter [mm]     | ~45      | ~100     | ~70      |
| Scanning Parameters |         |          |          |
| Energy [kV]       | 130      | 125      | 120      |
| Current [µA]      | 61       | 64       | 65       |
| Exposure time [ms]| 225      | 500      | 200      |
| Filter type       | brass 0.25 mm | brass 0.25 mm | brass 0.25 mm |
| Rotation step     | 0.1°     | 0.3°     | 0.2°     |
| Camera binning    | 4×4      | 4×4      | 4×4      |
| Dimension of projection image | 560×560 | 560×560 | 560×560 |
| Raw image resolution [µm/pixel] | 119.71 | 119.71 | 119.71 |
| Frame averaging   | 10       | 4        | 10       |
| Wide scan         | No       | Yes      | No       |
| Extended (vertical) scan | No    | Yes (4)  | No       |
| 360° scan         | No       | No       | Yes      |
Figure 1. (a, b) sample of concrete 1 (B1), (c, d) sample of concrete 2 (B2), (e, f) sample of concrete 3 (B3), (g) the SkyScan 117 Micro-CT scanning device (www.bruker.com).

Adjusting the scanning parameters i.e., the energy of the X-Ray source (kV), the current of the source (μA), the exposure time of the detector (ms), the X-Ray filter, the rotation step, and the amount of frame averaging accordingly, the good contrast ratio can be achieved. High energy, current and exposure time were used to reduce the noise. The brass-type filter is specifically used to diminish the noise of the low energy due to the wide frequency spectrum of the X-Ray source.

For all three samples, the scanning process uses the detector module option of producing standard quality image which can be obtaining by increasing the binning size of 4×4 with a corresponding image dimension of 560×560 pixels and spatial resolution of 20-140 μm. For sample B2, the wide scan was used where it was achieved by moving the CCD to the left and right position thus producing two half-sides projection images with dimension of 1056×560. As for the scan of B3, 360° scan was done by
extending the default rotation of 240° to a full rotation of 360°. This is particularly important to reduce streak effect which often appears for sample which composed of quite contrast range of density. As described in details in [12], the scanning process for all three samples were chosen to be conducted in low resolution mode but using low rotation step.

The scanning procedure generates raw projection images which are similar to X-Ray radiograph. These images are in 16-bit TIFF format. The whole 3D structure of the sample was obtained through the reconstruction (using the Feldkamp backpropagation algorithm [13]) which is done using NRecon software (Bruker Micro-CT). The NRecon uses the GPUReconServer which make use of the GPU (Graphical Processing Unit) processors to accelerate the reconstruction process. Pre-processing on the images was done to enhance the quality of the generated images by reconstructing one 2D visual of the trans-axial slice as a preview. From the preview, a fine tuning of the pre-processing parameters (post-alignment compensation, ring artefact reduction and beam hardening correction) was done mainly to perform artefact removal/reduction (see [12] for the detailed descriptions of these parameters).

The reconstruction process produces a stack of 2D slice in the z direction (x-y plane) in 8-bit greyscale images BMP format. The greyscale value (0-255) describe the relative density. By using this stack, qualitative analysis in 2D and in 3D can be done using Data Viewer and CTVox (Bruker Micro-CT). Quantitative characterization in this study was done by using CT-Analyser where a thresholding (binarization) of the greyscale images was done prior to analysing the pore. A global histogram-based semi-manual thresholding was chosen to distinguish the pre-from the solid structure inside the concrete samples. Subsequently, individual 3D particle analysis as well as the bulk volumetric 3D analysis were done on the binary image where the white (1) was assigned for pore structure and black (0) was assigned for the solid structure. Table 2 lists the parameters for the processing and the subsequent analysis.

| Parameter name, symbol and unit | Methods, parameter value |
|--------------------------------|--------------------------|
| **Basic Processing**           |                          |
| - Thresholding                 | global-histogram based (semi-manual), using Otsu method, followed by slight adjustment to conform with the visual observation of the structure. B1: 0-40; B2: 0-48; B3: 0-30 |
| - Despeckle                    | removing black/white speckles less than 9 voxels |
| **Image Analysis (3D bulk volumetric)** |                         |
| - Total bulk volume of sample (VOI), TV, mm³ | total bulk volume inside the of the VOI border. |
| - Volume of solid structure, Obj.V, mm³ | total volume of the solid within the VOI border. |
| - Volume fraction of solid structure, Obj.V/TV, % | ratio of the solid volume to the total bulk volume. |
| - Total Porosity, Po(tot), % | ratio of the pore volume to the total bulk volume. |
| - Average pore size, St.Sp, mm | thickness of the pores of the sample, measured based on method defined in [14-16]. |
| **Image Analysis (individual particle analysis of the pore objects)** |                         |
| - Particle volume (individual pore volume), PV, mm³ | volume of individual pore objects |
| - Normalized Centroid.z, Ctrd.z, mm | centroid of the particles (pore objects) in z direction, normalized to the height of the sample |
| - Major diameter, D, mm | diameter of an imaginary cylinder formed around the crest of an external thread of the pore objects |
| - Volume-equivalent sphere diameter, D, mm | diameter of a sphere having the same volume as the particle (pore objects) |
| - Sphericity, Sph, - | the measure of how closely the shape of an object approaches that of a mathematically perfect sphere |
3. Results and Discussions

The reconstruction process generates greyscale images as can be seen in Figure 2. Figure 2(a-c) shows the 2D view of the reconstructed images as horizontal plane (trans-axial view) and Figure 2(d-f) are the images obtained from vertical slicing (coronal view) for sample B1, B2 and B3 respectively. From these images, we can directly observe that sample B1 contains aggregate with various size and the density of the aggregates is quite similar to the cement. The aggregates are also observed to be randomly distributed throughout the sample. Pores can also be observed as black spots mostly appeared on the outer part of the aggregates. For sample B2 however, the solid mixture is almost homogeneous. Aggregates only appears in a small fraction. Pores are visually observed to be more dominant compared to the aggregates. Sample B3 shows more heterogeneous structure where the OPS aggregates have lower density compared to the cement, and pores were also distributed throughout the sample mostly on the surface of the OPS aggregates.

These patterns that were observed in the 2D visual can also be observed in the volumetric visual of the three samples can (see Figure 3 (a-c)). Figure 3 (e-f) is a composite visual where the solid was cut in-half and the pore objects were enhanced using distinctive colour rather than just dark space. It can be visually observed that all three samples have quite large fraction of pore space which are evenly distributed throughout the sample. The result of from characterization of the samples by means of image analysis (calculation of morphometric parameters), is presented in Table 3 for the bulk volume, and Table 4 for the individual particle analysis (pore objects). The results from the individual particle analysis can also be represented as histograms in order to observe the patterns and distribution (see Figure 4).

![Figure 2. Reconstructed images of the samples in trans-axial slices (a-c), and coronal slices (d-f).](image-url)
Figure 3. Volumetric 3D visual of the three samples (a) B1, (b) B2, and (c) B3, and the composite visual of the pore and the solid of sample (d) B1, (e) B2, and (f) B3.

Table 3. Calculated morphometric parameters for the corresponding scan modes.

| Parameter name, symbol and unit | B1       | B2       | B3       |
|---------------------------------|----------|----------|----------|
| Total bulk volume of sample (VOI), TV, mm$^3$ | 65,238   | 792,693  | 180,193  |
| Volume of solid structure, Obj.V, mm$^3$ | 64,694   | 786,191  | 177,462  |
| Volume fraction of solid structure, Obj.V/TV, % | 99.170   | 99.180   | 98.490   |
| Total Porosity, Po(tot), %      | 0.830    | 0.820    | 1.510    |
| Average pore size, St.Sp, mm    | 0.330    | 0.340    | 0.430    |

**Image Analysis (individual particle analysis of the pore objects): mean values**

| Parameter name, symbol and unit | B1       | B2       | B3       |
|---------------------------------|----------|----------|----------|
| Particle volume (individual pore volume), PV, mm$^3$ | 0.491    | 0.592    | 0.549    |
| Centroid.z, Ctrd.z, -           | 0.595    | 0.643    | 0.545    |
| Major diameter, Dm, mm           | 0.870    | 1.100    | 1.019    |
| Volume-equivalent sphere diameter, D$_E$, mm | 0.489    | 0.624    | 0.632    |
| Sphericity, Sph, -               | 0.787    | 0.680    | 0.809    |
From Table 3 it is shown that the three samples have very low porosity. Sample B3 has a slightly larger porosity compared to sample B1 and B2 due to the shape of the aggregates which are curved and buckled. This might cause air bubbles to have a higher chance to be trapped inside the mixture. Individual pore volume analysis and sphericity analysis which are presented as histogram in Figure 4 describe that all the samples have large number of small pores even though there are pores which have a considerable large in volume. The description of pore size was also described by the volume-equivalent diameter and the major diameter. Both of the average of these parameters shows quite small value, and by direct mathematical prediction, the diameters values are not in conform with the average of the particle volume. This should be analysed carefully due to the possibility of the actual distribution of the parameters rather than the average only. As can also be observed in Figure 4, the sphericity was dominated by high value, thus the pores are most likely to have near-spherical shape although there is small amount of pores that has very low sphericity.

With regards to the compressive strength, there is no distinctive pattern that is revealed related to the pore structure characteristics. This is due to the fact that the compressive strength itself is not solely depend on the pore space, but is mainly depend on the mixture (cement, sand, aggregates). Thus, for different type of aggregates, there is no unique correlation between the compressive strength with the pore structure characteristics. However, the pore size distribution pattern is similar to the analysis from a research by Lu et al., [17] where the small pores dominate the samples. Bossa et al. [18] also analysed nano-scales aperture diameters which shows quite similar results.

**Figure 4.** (a) Histogram of the distribution of individual particles (pore) volume analysis, (b) histogram of the distribution of particle (pore) sphericity.

4. **Conclusion**

Three different concrete sample has been scanned and the pore structure of the samples has been analysed by means of digital image processing and analysis method. Bulk 3D volumetric analysis is able to provide a rough description of the sample, although the detailed depiction of the pore structure through performing the individual particle analysis is more accurate. In analysing the result of the latter calculation, one should be careful since variability of the calculated parameters could be very high, and that the distribution of certain parameters might not be normal. Elaborated analysis using more detailed statistical tool and descriptor such as histograms accompanied by box-plot should provide a more sophisticated analysis regarding the characteristic of the samples. Future development of this analysis can be focused towards studying the correlation between these micro-structural parameters with macro-properties of the sample, such as the strength and other elastic properties.
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