Digital 3D Microstructure Analysis of Concrete using X-Ray Micro Computed Tomography SkyScan 1173: A Preliminary Study

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Abstract. Digital imaging of a concrete sample using high resolution tomographic imaging by means of X-Ray Micro Computed Tomography (µ-CT) has been conducted to assess the characteristic of the sample’s structure. A standard procedure of image acquisition, reconstruction, image processing of the method using a particular scanning device i.e., the Bruker SkyScan 1173 High Energy Micro-CT are elaborated. A qualitative and a quantitative analysis were briefly performed on the sample to deliver some basic ideas of the capability of the system and the bundled software package. Calculation of total VOI volume, object volume, percent of object volume, total VOI surface, object surface, object surface/volume ratio, object surface density, structure thickness, structure separation, total porosity were conducted and analysed. This paper should serve as a brief description of how the device can produce the preferred image quality as well as the ability of the bundled software packages to help in performing qualitative and quantitative analysis.

1. Introduction

Imaging technique for characterization of various type of materials has been advancing in a fast progress along with the development of instrumentation and computer technology. Among the widely used imaging instrument is the X-Ray Micro Tomography Scan (µ-CT). This device has been employed in various field of research such as for digital rock analysis for numerous application such as calculation of porosity, permeability, simulation of fluid flow and various structural description [1-5]. In life science, the method has been applied for various dentistry researches [6-8] as well as bone research. [9-11]. In building materials researches, the µ-CT has been utilized for investigating self-sealing in concrete materials [12], porosity and characterization of building stones microstructure [13], and investigation of water repellent and consolidants in natural building stones [14].
This paper is aimed to present an application of µ-CT preliminary analysis on concretes using specific device, i.e. the Bruker SkyScan 1173 X-Ray µ-CT. Procedure of obtaining images through three main stages and the adjustment of corresponding parameters are presented. Qualitative analysis is discussed briefly to describe the capability of the device and the bundled software package.

2. Sample and Method
In this study, a concrete core sample was obtained from an existing building in Jakarta. The sample has a diameter of 1.5 inch and a height of 6.5 cm which was taken by a coring machine from a beam structure (see Figure 1.a.). The sample was scanned using Bruker SkyScan 1173 High Energy Micro Computed Tomography scanning system (Figure 1.b.). Based on the X-Ray attenuation by the sample which is recorded by a flatpanel detector, the device is able to produce microstructural 3D image of the sample. The SkyScan 1173 device is mainly consist of three modules, i.e., the X-Ray source, a rotating sample stage and a CCD flatpanel detector which record and convert the attenuated X-Ray signal into digital image. The tomography concept applied in the system requires the sample to be rotated at a minimum rotation of 180° during the scanning process with the rotation step adjusted according to the chosen image resolution.

Figure 1. (a) sample of concrete, (b) the SkyScan 117 Micro-CT scanning device (www.bruker.com).

The detector module of SkyScan 1173 has the ability to produce three different image quality: standard, medium and high which are specified as follows:
- high quality image is produced by using the 1×1 binning system where the process generates a raw projection image with dimension of 2240×2240 pixels and spatial resolution of 5-35 μm,
- medium quality image is produced by increasing the binning size of 2×2 thus generated image with dimension of 1120×1120 pixels and a spatial resolution of 10-70 μm,
- standard quality image is produced by increasing the binning size of 4×4 with a corresponding image dimension of 560×560 pixels and spatial resolution of 20-140 μm.
The resolution of the image is determined by the position of the sample and the desired field of view (FOV) on the sample. The FOV for a single-scan mode is determined by multiplying image dimension with the desired resolution, thus for example, the highest resolution image will have a FOV of (2240×2240)×5 µm = (11.2×11.2) mm. For a large sample (up to a maximum diameter of 14 cm and height of 18 cm), SkyScan 1173 system provide extended capability of non-single-scan modes, i.e., the wide scan, a (vertically) oversize scan, and the combination of both. Wide scan is achieved by moving the CCD to the left and right position thus producing two half-sides projection images with dimension of 4480×2240. Oversize scan is done by moving the sample holder vertically. Another possible mode is the spiral scan where the scanning process is done by rotating the sample holder and at the same time moving the sample holder vertically thus producing a spiral movement.

Producing a good 3D image of the structure means generating images with a good contrast ratio of the components and the high signal to noise ratio. By adjusting the scanning parameters, which are the energy of the X-Ray source (in kV), the current of the source (in µA), the exposure time of the detector (in ms), the type of X-Ray filter, the rotation step, and the amount of frame averaging accordingly, the good contrast ratio can be achieved. For a high density sample such as concrete, a high energy X-ray is required as well as a high current and exposure time to reduce the noise. Brass-type filter is also required to reduce the noise produced from low energy X-Rays. In this study, the sample was scanned using three different sets of parameters. The adjusted scanning parameters for each scanning process are listed in Table 1.

| Parameter               | Scan 1     | Scan 2     | Scan 3     |
|-------------------------|------------|------------|------------|
| Energy [kV]             | 100        | 130        | 130        |
| Current [µA]            | 40         | 61         | 61         |
| Exposure time [ms]      | 125        | 225        | 1500       |
| Filter type             | brass 0.25 mm | brass 0.25 mm | brass 0.25 mm |
| Rotation step           | 0.3°       | 0.1°       | 0.2°       |
| Camera binning          | 4×4        | 4×4        | 1×1        |
| Dimension of projection image | 560×560     | 560×560    | 2240×2240  |
| Raw image resolution [µm/pixel] | 89.78   | 119.71     | 9.98       |
| Frame averaging         | 10         | 10         | 10         |
| Wide scan               | Yes        | No         | No         |

For Scan 1, the sample was positioned to be quite close to the source. For Scan 2, the sample was scanned in a position where the total height of the samples is within the field of view (FOV) of the CCD. For Scan 3, the sample is positioned as close as possible to the source thus producing highest resolution, however in this scanning mode, the produced image is the centre (partial) volumetric region of the sample.

From the scanning process, raw projection images were produced. These images are basically similar to the ones obtained from X-Ray radiograph which display the attenuated X-Rays that are captured by the detector. The images portray the nature of the sample’s structure vaguely, because they display the projected structure in 2D space. A complete 3D structure of the sample can be further obtained by performing a reconstruction of the projection images (sometimes also referred as sinograms) which is basically a numerical inversion based on the Feldkamp backpropagation algorithm. The reconstruction is done by the NRecon software (Bruker Micro-CT) which uses the GPUReconServer that utilizes the GPU processors to accelerate the core reconstruction process. During this process, several parameters can be adjusted to enhance the quality of the generated images. The adjustment of these parameters level can be done by first performing a reconstruction of one 2D visual of the trans-axial slice as a preview. A fine tuning of the parameters can be done by NRecon to ensure that the artefact removal can be done accurately. The parameters are as follows:
1. Post-alignment/misalignment compensation, which is basically a correction of raw image position that might be caused by object’s movement during the scanning process.

2. Ring artefact reduction. A process of removing circular noise/pattern which is basically appears due to rotating sample. The level of this artefact might vary according to sample and holder state. Increasing the number of random movement usually decrease the level of the artefact quite significantly.

3. Beam hardening correction. Beam hardening artefact appears in the reconstructed image mainly caused by the density or the attenuation coefficient of the sample. Most high density objects that are scanned using SkyScan 1173 shows the pattern where the centre part of the sample usually has significantly lower grayscale value compared to the ones in the outer part of the image.

4. If the object is larger than the field of view, an option named ‘Object Bigger Than FOV’ should be selected, and the contrast ratio of the generated image would be enhanced.

Other parameter that can be adjusted during the reconstruction process is the reconstructed image pixel size. This option provides the possibility of producing reconstructed images with lower spatial resolution compared to the one that was adjusted for the scanning process. This can be done by means of undersampling method which is basically a method of choosing the voxel size of the reconstructed image and then pixels of the raw projection images are backprojected into that chosen area during the reconstruction process [15]. A smoothing can also be done if necessary, and the suitable amount of smoothing can be adjusted by observing the preview image. The smoothing reduces noise, however, the use of the smoothing kernels (Box (asym.), Box (sym.), and Gaussian) it might also promote blurring for highly detailed structures. A certain degree of static rotation can also be selected if we want to produce a reconstructed image that has different angle with the actual angular position of the scanned sample. Another important thing to consider is that the reconstruction process is done using real number (floating-point) while the produced images consist of integers where the range is determined by the output file format. The default output format is 8-bit BMP, which means that the output voxels have the value between 0 and 255. The dynamic range of data of the image can be tuned by adjusting the range from the histogram of the previewed slice.

The output from the reconstruction process is a series of greyscale images, which is a stack of 2D slice in the z direction (x-y plane) or most of the time referred as trans-axial images. These 8-bit images contain data of relative density which represented by the voxel value of the images. Qualitative analysis through visual observation can be done in 2D, orthoslice view, as well as in 3D volumetric rendered images. Quantitative characterization is commonly done on binary images, which mean that the grayscale image needs to be converted through thresholding process. Various thresholding scheme are available in CTAn software and they can be generally categorized into global histogram-based thresholding and local-adaptive threshold. Depending on the nature of the samples, both of them can be chosen appropriately. Using the binary images, various characterization of the sample can be done. Table 2 lists the common characteristics that can be measured using CTAn software.

3. Results and Discussions

Scanning process produces a series of raw projection images in 16-bit TIFF file format. The preview of the images can be seen in Figure 2 (a,b,c). The interior microstructure of the sample can’t be observed only from these images. By reconstructing the projection images, we obtained the grayscale images as shown in Figure 2 (d,e,f). The 2D slices of Figure 2.d-f were chosen for the approximately the same vertical position. We could see a similar structure appeared in these images. Scan 1 and Scan 2 covered the same area but they had difference in the resolution and the rotation step during the scan.

The result from Scan 1 and Scan 2 showed a compatible comparison which involves the effect of X-Ray energy source, rotation step and the resolution. Scan 1 was done using energy of 100 kV while Scan 2 using 130 kV. Scan 1 was rotated through a rotation step of 0.3° while Scan 1 was scanned using rotation step of 0.1°, and the voxel size of Scan 1 is ⅔ that of Scan 2.
Table 2. Some typically calculated morphometric parameters.

| Parameter name, symbol and unit | Brief description |
|---------------------------------|-------------------|
| Total VOI volume, TV, mm\(^3\)  | Total volume of the volume-of-interest (VOI), measured using marching cubes volume model approach. |
| Object volume, Obj.V, mm\(^3\)  | Total volume of the solid within the VOI, measured using marching cubes volume model approach. |
| Percent object volume, Obj.V/TV, % | Ratio of the solid volume to the total VOI. |
| Total Porosity, Po(tot), %      | Ratio of the pore volume to the total VOI volume, expressed in percent. |
| Total VOI surface, TS, mm\(^2\) | Surface area of the total 3D VOI, measured by marching cubes method. Very useful for irregular VOI. |
| Object surface, Obj.S, mm\(^2\) | Surface area of the 3D solid objects inside the VOI, using the marching cubes method. |
| Object surface/volume ratio, Obj.S/Obj.V, mm\(^{-1}\) | Specific surface area: ratio of the solid wall surface the total measured VOI. |
| Object surface density, Obj.S/TV, mm\(^{-1}\) | The ratio of surface area to total VOI volume. |
| Structure Thickness, St.Th, mm   | Thickness of the solid part of the sample, measured based on method defined in [16], [17] and [18]. |
| Structure Separation, St.Sp, mm  | Thickness of the void space which is measured by the same method to the measurement of the structure thickness which applied to the void voxels. |

Generally, higher resolution provides better result in terms of quality, however from this comparison we could observe that the rotation step also gave significant effect to the reconstructed image. By doing the scan using higher rotation step, it is shown that certain kind of noise is introduced in the final reconstructed image. This is shown by unsmooth image of Scan 1. Comparing Scan 1-2 to Scan 3 (Figure 2f.), it is obvious that lower binning of the camera produces better image in terms of the depicted details of the composing objects as well as the sharpness of the object boundaries. These pattern is also observable in the 3D visual of the samples.

Volumetric visual of the three sets of digital data are shown in Figure 3. We can see from Figure 3 that each scanning mode produced different quality. Scan 1 provided a slightly better detail compared to Scan 2, however Scan 1 introduce noise that reduces the sharpness of the image. In addition to that, lower energy of the X-Ray source used in Scan 1 caused the luminosity of image to be lower (the image appear darker) compared to image obtained from Scan 2. This pattern appeared in both the 2D and 3D visual (Figure 2 and Figure 3).

Afterwards, quantitative analysis can be done by picking out the proper VOI and performing appropriate thresholding (binarisation) method. For the samples, VOI selection was done using regular cylindrical sample which clipped a small amount of outer area of the sample, especially for Scan 1 and Scan 2. Sequentially, automatic thresholding using global Otsu method was applied on the digital samples. The 3D analysis was later conducted using CTAn software and several characteristics are measured and listed in Table 3. Several discrepancies of the parameters were observed. A more elaborated analysis of the measured characteristic in the context of different resolution is required to decide which result to use according to a specific intention. Such analysis was already performed in rock sample by Latief et al. [19].

As an additional analysis of the sample listed in Table 3, some simple and direct measurement can also be done on the grayscale image, such as measurement of length and angle of orientation as shown...
in Figure 4. CTAn provides several ways of conducting such simple measurements on the grayscale image.

![Image](a) ![Image](b) ![Image](c)

**Figure 2.** Projection image of the three scanning modes (a) Scan 1, (b) Scan 2, and (c) Scan 3.

![Image](d) ![Image](e) ![Image](f)

**Figure 3.** Volumetric 3D visual of the three scanning modes (a) Scan 1, (b) Scan 2, and (c) Scan 3.

Other facts that needs to be put into a consideration is that a certain scanning mode is highly related to certain needs in investigating the structure. In our case, the highest resolution (Scan 3) was obtained by placing the sample in a very close position thus only display a partial area of the sample. In contrast to Scan 3, Scan 2 provide a description of the whole sample. Scan 2 has lower resolution compared to Scan 3, which means, some details would not be able to be analysed only by using data from Scan 2. Considering that, the data that was generated from Scan 3 must also be carefully interpreted. In Figure 2.f a thin gap is visible across the diameter of the sample. We must be careful not to hastily interpret this as a fracture inside the sample. If we observe carefully the image from Scan 1 and Scan 2, this gap...
is actually a border of a large aggregate which could not be visualized on the whole due to its size which is larger than the designated FOV.

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

| Parameter name, symbol and unit | Scan 1          | Scan 2          | Scan 3          |
|---------------------------------|-----------------|-----------------|-----------------|
| Total VOI volume, TV, µm³       | 5.23×10¹³       | 6.13×10¹³       | 6.80×10¹²       |
| Object volume, Obj.V, µm³       | 5.16×10¹³       | 6.04×10¹³       | 5.07×10¹²       |
| Percent object volume, Obj.V/TV, % | 98.33          | 93.72          | 74.57          |
| Total VOI surface, TS, µm²      | 8.08×10⁹        | 9.27×10⁹        | 2.06×10⁹        |
| Object surface, Obj.S, µm²      | 1.48×10¹⁰       | 2.79×10¹⁰       | 1.83×10¹⁰       |
| Object surface/volume ratio, Obj.S/Obj.V, µm⁻¹ | 2.88×10⁻⁴       | 4.62×10⁻⁴       | 3.60×10⁻²       |
| Object surface Density, Obj.S/TV, µm⁻¹ | 2.83×10⁻⁴       | 4.33×10⁻⁴       | 2.69×10⁻²       |
| Structure Separation, St.Sp, µm | 1.22×10³        | 8.60×10²        | 8.13           |
| Total Porosity, Po(tot), %      | 1.67            | 6.28            | 25.43          |

**Figure 4.** Measuring the distance between two points (length of an object) inside the sample as well as the angle of orientation. Graph on the right is the grey-level value of the pixels along the yellow line.

From Table 3 we can also see the pattern of the measured (calculated) parameters which are highly dependent to the resolution (or to be exact, the quality) of the produced image dataset. In other words, thorough analysis should be taken carefully in order to produce accurate measurement and interpretation of the sample. Other various possible scanning modes or schemes are also important to be studied in order to obtain a more detailed insight of what could be achieved from each of the scanning schemes.

### 4. Summary

Procedure of conducting digital analysis on a concrete sample using Bruker SkyScan 1173 has been presented. Three different sets of scanning parameters were used to provide a depiction of how the produced images was affected by the parameters as well as to deliver a brief portray of what sets of parameters should be adjusted for a particular purpose. Brief qualitative analysis through visual inspection and quantitative analysis via some calculated parameters were presented. We can summarize that higher resolution does not always guarantee to generate images which can display good detail of the sample. This paper should serve as a brief description of how the device can produce the preferred image quality as well as the ability of the bundled software packages to help in performing qualitative and quantitative analysis.

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