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X-ray computed tomography: Image processing and applications

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Micro Abstract
Understanding the mechanical behavior and deterioration processes of inhomogeneous cement based materials such as mortar and concrete can be improved with information on their inner structure obtained in non-destructive x-ray CT scans. However, the different concrete components have similar attenuation coefficients, resulting in low contrasts between them. It requires demanding image processing techniques, of which a selection will be presented in relation to their applications.

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Introduction

Concrete is a heterogeneous material whose mechanical, physical and chemical characteristics can strongly change depending on its components (cement, water, aggregates, additives, and admixtures). The cement, the water amount, and also the aggregate form and distribution, affect durability and mechanical behavior of concrete.
Fundamental for the investigation is to define the analysis scale: it is possible to analyze the material from macro scale to micro scale, always depending on the object of research. In macro scale the concrete can be analyzed as a homogeneous material, in meso scale it is possible to distinguish aggregate, cement paste, and air voids (see figure 1) while the micro scale resolution, e.g., also accounts for the cement paste characteristics.

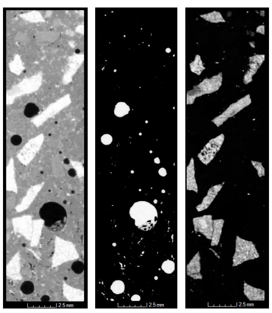

Figure 1. Tomography representation of a concrete cylinder (left) and air voids (center). Common image processing can lead to a partially segmentation of the aggregates (right).

In this paper, we will concentrate on the segmentation of the phases in meso scale, aimed to obtain information on mechanics and durability. Computed tomography (CT) technology allows the inspection of specimens' internal structures with a non-destructive method, revealing very detailed information not detectable with common test setups. To define concrete peculiarities, the focus lays on the attenuation coefficient of its components. In the following, some application on the segmentation of aggregate and air voids will be shown as well as a procedure to identify the steel fiber amount in Ultra High Performance Fiber Reinforced Concrete (UHPFRC).

1 Image Processing

The investigation of scanned objects requires elaborate processing and interpretation of the images with different techniques. The first step is the 3D volume reconstruction from the x-ray sinogram. This step already determines a variety of parameters that will later influence the image processing possibilities, e.g., image depth (number of gray levels) and artefact suppression. The gray levels are distributed in the reconstructed volume according to the specimen's materials attenuation coefficients. For the common cone beam analysis, an attenuation coefficient is assumed; the parameter is calculated as a function of density, atomic number, energy of the cone beam and dimension of the object (see [2]).
The image processing procedures commonly used to segment a tomography can be distinguished in threshold-, edge detection- and region based-techniques. Usually a combination of methods is used together. The threshold methods, the most common histogram-based procedure, are used to separate some component (foreground) from the rest of the image (background). These methods are particularly efficient when the attenuation coefficients of the components of an object are strongly different. This can be the case for composite materials, e.g., reinforced concrete.

2 Steel fiber content

In the case of UHPFRC, image processing of computer tomography allows to define content, distribution and the orientation of the fibers. Already some authors deal with this topic, for example [3, 7]. For this application, a parametric threshold method is applied.

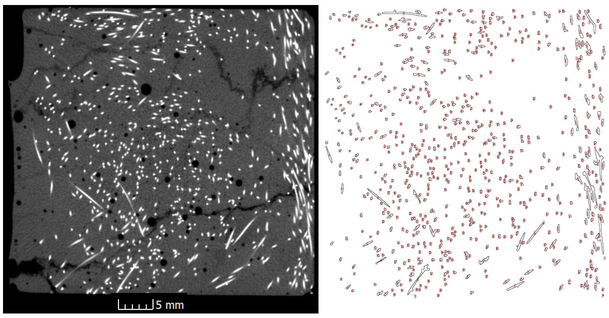

Figure 2. Section tomography of a prism (40x40x160mm) (left) and relative steel fibers detection (right). In black the recognized fibers, in red the numeration index. [6]

Starting from a known fiber content defined in advance, a (parametric) threshold level is set. Acting on the foreground elements, the geometrical characteristics of the fibers are analyzed: ellipsis axis, center of gravity and orientation angle are calculated for every single fiber. To avoid artifacts, a further geometrical filter, checking length and brightness, is applied. Based on this procedure, it is possible to define coefficients that express the fibers global orientation. A representation of the process is presented (see figure 2). Nevertheless, the procedure delivers results that can be compared to other measurement techniques ([9]), the overlapping fibers are a challenge in this context.

3 Porosity

Threshold methods are an efficient way to segment concrete or cement paste, not only for fibers with higher but also for phases with lower attenuation coefficients. The big difference in the gray level histogram between air and the material for the solid phase allows an easy threshold based segmentation of air voids. Porosity characterization is a topic with a wide research interest [4, 8] due to its high effect on concrete durability characteristics. Similar to the fibers, air voids can be characterized with respect to their geometrical properties or their distribution in the scanned volume.

4 Aggregate Segmentation

The need for an accurate representation of aggregate geometry arises from different necessities. For example, the inner and realistic geometry of the specimen is required for successive meshing and correct modeling in finite element analyses [5]. These methods could be applied in validation tests with special testing modules in CT machines, where specimens are scanned under different loading conditions. An appropriate automatic image processing procedure can detect the displacement of the aggregate giving further information on the deformation and stress distribution.

Mechanical aspects of concrete are strongly affected by the aggregate type. Aggregates are available in different dimensions, densities and chemical compositions. It is possible to investigate the attenuation coefficient of the aggregates in a concrete specimen, but it is complicated to segmentate the aggregates from the cement, because in most of the cases the attenuation coefficients of the cement components have similar magnitude. On the other hand, the aggregates are not homogeneous and it reveals difficult to define their geometry.
To address this problem, it is possible to apply advanced image processing techniques. These, however, are not easy to automatize for a multitude of scans as they often present different component characteristics. As a first step towards the automatic segmentation procedures, we casted several concrete specimens with different aggregate types available in Germany (table 1). Afterwards the specimens were scanned, reconstructed, filtered and with histogram-based techniques segmented.

Table 1. Ordinary concrete aggregates, density ordered [1].

Common aggregate		**Heavy aggregate**	
Quartzite sand	(2,6...2,7) kg/m^3	Baryte	(4,0...4,3) kg/m^3
Limestone	(2,6...2,8) kg/m^3	Ilmenite	(4,6...4,7) kg/m^3
Granite	(2,6...2,8) kg/m^3	Magnetite	(4,6...4,8) kg/m^3
Basalt	(2,9...3,1) kg/m^3	Hematite	(4,7...4,9) kg/m^3

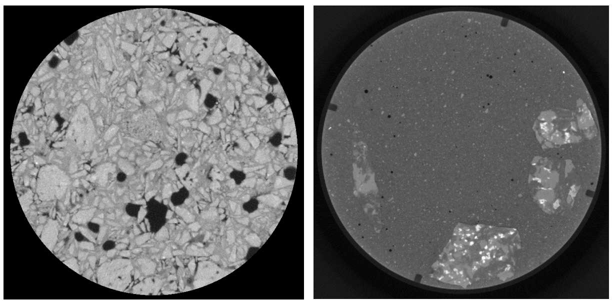

Figure 3. Tomography section of basalt aggregate (left) and diabase casted concrete (right).

The basic idea of the procedure is to cast concrete with heavy aggregates that can easily be segmented from the cement matrix. The normal limestone, quartzite sand, and alluvial aggregate, commonly used to cast concrete, has similar attenuation coefficients as cement paste. With heavy weight aggregate concrete, used for radiation protection walls, for example, for nuclear power plants, a great difference in the attenuation coefficients between concrete components can be reached. However, for excessive contrast differences artifacts, decreasing image quality can be observed (e. g. baryte aggregate, s. figure 4). To identify aggregates with high contrast and negligible artifacts production we casted different high-density aggregate concrete for CT scans. With this study, we were also able to confirm the physical effects between the x-rays and matter with image data of baryte (higher atomic number and lower density) and hematite (lower atomic number and higher density) aggregates (see figure 4).

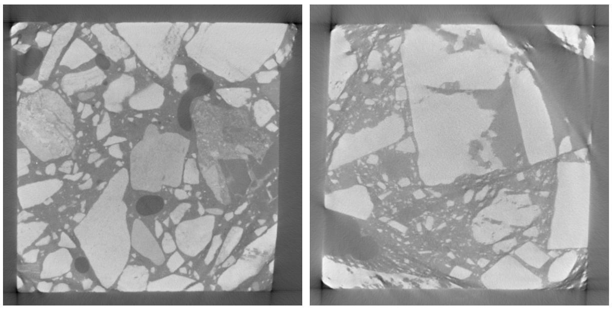

Figure 4. Heavy aggregate concrete. CT scan section of a (left) hematite- and a (right) baryte-casted concrete.

To find a well-balanced setup resulting in a simplified segmentation without disadvantageous effects represent a challenging research object. Between the heavy aggregate and common aggregate, a group of aggregates could be defined, that has moderate density (2,9. . . 3,0 kg/m^3), allowing a segmentation without detrimental artifacts.

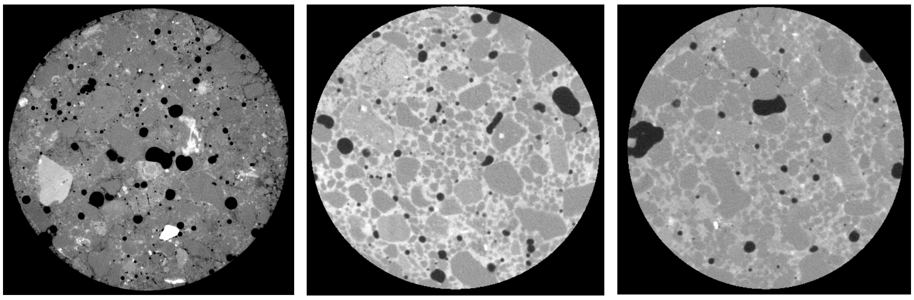

Figure 5. Common concrete Tomography section (left), concrete whose cement paste are mixed with Iopamidol (center) and Potassium Iodide (right).

Other procedures with the goal of contrast enhancement where also conducted, using radiocontrast, e.g., agent like non-ionic compound, potassium iodide and barium sulfate (some examples given in figure 5). These compounds, in powder or in liquid form, are able to enhance the attenuation coefficient of the cement paste. The percentage of the compound necessary to obtain an easy segmented representation is still under investigation.

Conclusions

In the last years a growing number of studies focused on computer tomography and image processing hence methods but also the interpretation are continuously improved, already allowing to draw robust conclusions data generated by x-ray computed tomography. As discussed above, some methods have already found application in material science, e.g., the identification of steel fibers, air voids. Nevertheless, there are still some issues open. Imaging and image processing techniques must be used symbiotically with the knowledge of the examined materials in order to achieve the best possible results. Especially the development of automatic procedures is hardly possible without relying on both domains.

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