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The application of Computed Tomography for characterising the pore structure of building materials

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ABSTRACT
Flow and transport phenomena in porous media play a significant role in various fields of science and technology, comprising a spectrum from medical sciences over material sciences to soil and rock sciences. Also in building materials, the transfer of moisture and heat play a crucial role when assessing their properties and performances. Hence, three-dimensional analyses of the pore structure of building materials are becoming progressively more important in recent years, to obtain more accurate interpretations and simulations of their characteristics. Computed tomography has proven to be an excellent and versatile tool to perform these analyses non-destructively. The reconstruction of the pore structure is of high importance for establishing accurate models, as it plays a crucial role in determining important characteristics of building materials. These models allow to better understand the results of corresponding laboratory tests and in the near future might replace these time consuming experiments. In this paper the added value of Computed Tomography characterization will be demonstrated based on two case studies. The first will focus on the accurate simulation of moisture transfer while in the second one CT datasets are used to overcome a multiscale problem regarding the simulation of the effective thermal conductivity.

KEYWORDS
Micro-CT, Pore network properties, Hygric properties, Heat transfer simulation

INTRODUCTION
Three-dimensional characterizations of the pore structures of building materials are becoming progressively more important in recent years, in order to obtain more accurate interpretations and simulations of their properties and performance characteristics. This study focuses on two applications where pore-scale-based simulation is distinctively an added value: moisture flow and heat transfer. In both cases the accuracy of the pores-scale models greatly depends on the input parameters i.e. the geometry of the solid matrix material or the corresponding pore network. This paper will focus on the data acquisition part of the process and show the possibility's regarding pore shape description and the incorporation of multi-scale datasets.

Storage and transport of moisture in porous media play a significant role in the performance characteristics of building materials. Moisture is therefore often a critical factor when judging the durability and sustainability of built structures and the health and comfort of building occupants, and a reliable evaluation of moisture transfer in building materials is crucial for correct performance assessments. In order to determine the moisture behavior of building components, numerical simulation models are commonly used. However, these models require a good description of the moisture retention and moisture permeability functions, as these are crucial input data for a dependable simulation (Dong and Blunt, 2009).

Heat transfer through building materials and building components equally is important. These transfers make up a crucial part of the energy consumed for the conditioning of residential buildings. Porous building blocks, consisting of gas-filled pores in a solid material matrix, are therefore increasingly used in residential buildings, combining ease of construction and adequate mechanical properties with a relatively high thermal resistance. However, due to increasingly stringent energy requirements, further reduction of the thermal conductivity of these materials is needed to improve their performance and boost their application (Coquard and Baillis, 2009).

DATA ACQUISITION

Micro-CT

The working principle of CT scanners is schematically depicted in Figure 1. The attenuation of X-rays when passing through the material is recorded for multiple rotation angles. Because the attenuation depends on the interior composition of the sample, it is possible to reconstruct this internal information from X-rays that have travelled a different path through the sample. The generated X-rays are attenuated by the components of the sample and captured by the detector, generating projection images. Image reconstruction is a mathematical process, which calculates the CT slices based on the projection images using a back projection algorithm. The data at one pixel in one projection image comes from the attenuation of the object along the entire path from source to detector, explaining the need for multiple rotation angles and projections. The result of the reconstruction process is a 3D image stack of gray-scaled voxels.

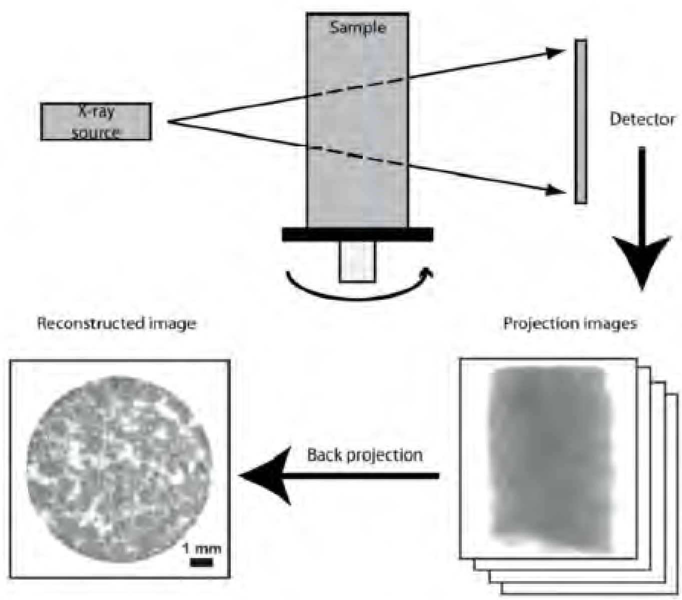

Figure 1. Schematic overview of the working of a CT scanner. The X-rays are generated in the source, travel through the object where they are attenuated and are captured by the detector.

Segmentation

In order to differentiate gas pore from solid matrix voxels, an image segmentation needs to be performed. Quantitative analysis of the porosity requires a voxel by voxel determination of it belonging to pore or solid phases. For segmentation an in-house dual-thresholding algorithm is used. This method is an adaptation of the single-threshold approach, which typically selects pixels/voxels on the basis of their unique histogram range. However manually determining the boundary values is not straightforward in the case of insufficiently ideal histograms, with peaks that are not obviously separated. The applied dual or hysteresis thresholding uses two intervals of the histogram in order to determine the segmentation. Voxels corresponding to the first 'strong' threshold are classified as foreground voxels, while voxels selected by the second threshold are only considered foreground if they are connected to voxels already selected by the 'strong' threshold. The advantages of this algorithm are the reduced sensitivity to residual noise in the dataset and the selection of less insulated foreground voxels. However this method does not exclude operator bias when determining the threshold values which will have a significant influence on the results. Baveye et al. (2010) provide an excellent illustration on how inter-operator bias can influence the thresholding results. 13 experts where asked to segment a micro-CT image of a soil sample and the obtained porosity results varied between 0.13 and 0.72 with a standard deviation of 0.14. Hence, this inter-operator bias will have an important influence on the characterization of the studied material or interpretation of the results.

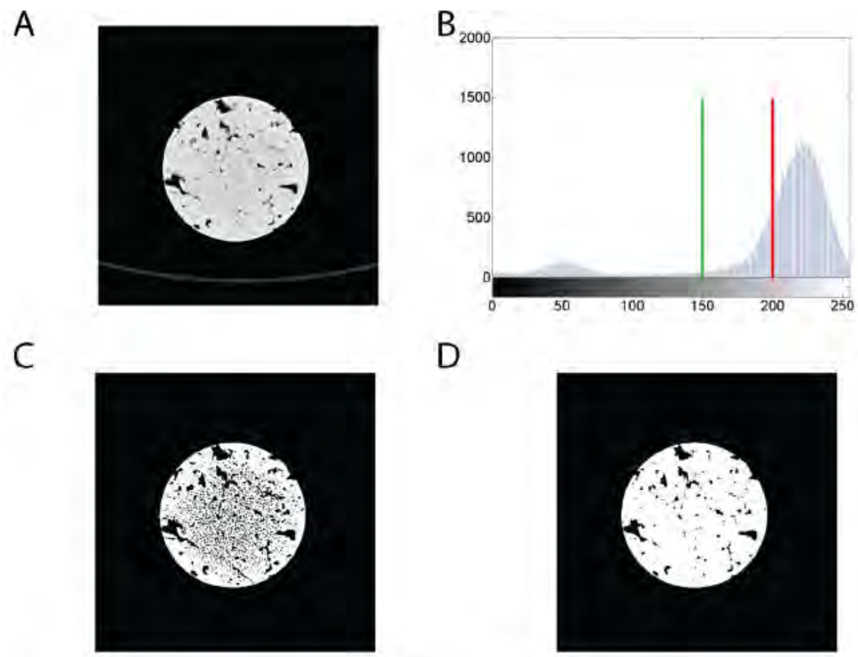

Figure 2. Dual thresholding: a) Original slice, b) Histogram of the attenuation coefficients; the strong threshold is indicated in red; the weak threshold is indicated in green, c) Matrix selection using only the strong threshold, d) Resulting slice using both the strong and weak threshold.

APPLICATIONS

The segmented images provide the input information for both applications. When simulating moisture flow, the pore space needs to be characterised as accurately as possible by generating a pore network model (PNM). For the simulation of heat transfer, the pore space as well as the solid matrix need to be incorporated in the model. Both applications are discussed below.

Fluid flow

The pore space in a sample can be represented as a network of pores (larger void spaces) and throats (smaller void spaces connecting the larger pore spaces). CT datasets form the ideal tool to characterise both components up to the scan resolution. The visualised pore network is

transformed into a pore network model (PNM) which represents the studied pore structure as accurately as possible while retaining a certain simplicity by representing each component of the network by a set of parameters such as volume, surface area and shape descriptors. Hence, the PNM tries to capture local features of the pore-space which are important for the fluid storage and transport processes under investigation.
Subsequently these PNMs are subjected to invasion algorithms that replicate different (de)saturation procedures: absorption, desorption, imbibition and drying. For unsaturated moisture storage and transport in building materials, Islahuddin and Janssen, (2017) developed a multi-scale hygric pore-scale simulator comprising the coexisting liquid and vapor phases of water. Hence in theory, PNMs form the basis of simulations which determine the moisture storage and moisture transport in building materials over the whole capillary range, allowing a complete and accurate determination of the hygric properties of building materials.

As an example a PNM has been generated for a sintered glass volume. This material is chosen because the entire pore size distribution can be captured by a 2.5 µm resolution micro-CT scan (Figure 3 A). The CT dataset also allows to mathematically describe the shape of the pore bodies based on the length of the three principal axis (Figure 3 B) (Claes, 2015). Because the pore shape distribution in the sample is homogeneous a PNM can be used to determine the hygric properties of the sintered glass. Based on the code of Islahuddin and Janssen, (2017) the permeability and adsorption curves can be calculated for the entire water saturation range (Figure 3 C and D).

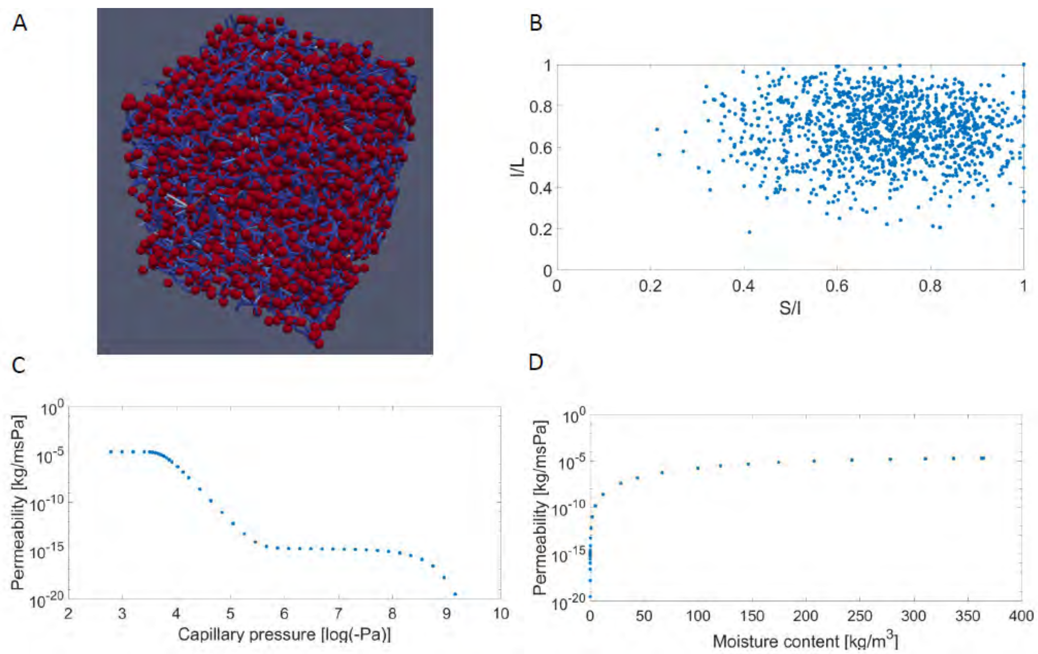

Figure 3. Sintered glass: a) Pore Network Model, b) Pore shape analysis, c&d) Adsorption permeability curve.

To assess the accuracy of the simulation, the obtained saturated permeability is compared with lab measurements. The simulated and measured saturated permeability are in the same order of magnitude, but the simulated one is slightly higher than the measured one: 1.86 10^{-5} vs 1.25 10^{-5} kg/m s Pa respectively. This trend was also observed by Oren & Bakke, (2003) and Dong & Blunt (2009), who performed simulations on the Berea sandstone and noticed a discrepancy around a factor 2 between simulations and measurements. This factor can be explained by the heterogeneity of the sample and the uncertainty associated in the course of imaging and image processing.

Heat transfer

One of the main advantages of micro-CT is its flexibility regarding sample size. Optimal sample diameters range between 1 mm and 4 cm. However, an inherent characteristic of CT is the negative relationship between scan resolution and sample size. The larger the sample, the bigger the voxel size becomes. Several materials, including building materials, often have a broad spectrum of pore sizes, ranging from nanometers to millimeters. The presence of multiple pore-scales in the studied sample can severely influence its physical properties. In order to test the applicability of CT on different scales, Reapor is chosen as a test case. Reapor is a highly-porous material mainly applied for acoustic absorption. The production process is based on recycled glass and consists of sintering together expanded granules, hence leading to a pore structure with a two-scale type of pore volume distribution: a cellular structure inside the granules and a granular structure overall. As there is a clear separation between the intra- and intergranular pore structures, a hierarchical approach is adopted to overcome the two-scale nature of the material: simulation results obtained on the intragranular level are averaged and used in the simulations performed on the intergranular scale.

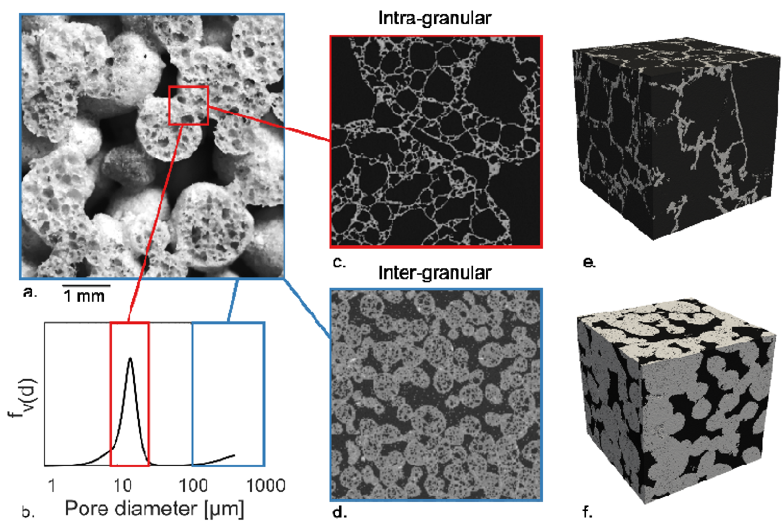

Figure 4. a) Photograph of sample pore structure with the bimodal pore volume distribution clearly visible, b) Measured pore volume distribution of the Reapor material, c&d) Micro-CT slice scan result of the intra- and inter-granular scale, e&f) Segmented 3D image of intra- and inter-granular scale scans (after Van De Walle et al, 2018).

In order to characterise the intra-granular scale a 2 mm diameter sample is scanned at a resolution of 1.2 µm. Based on these results simulations were conducted and the results are shown in Figure 5 A. A power-law trend-line is fitted through the results, showing an expected decrease of the thermal conductivity with increasing porosity.

Subsequently these values are used to characterize the matrix material when analyzing the inter-granular pore network. The configuration of the matrix material is characterized by a 12 µm resolution scan. The results of these simulations are shown in Figure 5 B. In order to assess the quality of the simulations, the results are compared to lab measurements and information provided by the manufacturer. On average, the simulations show a relative deviation of about 5 % with the experimental measurements, indicating a good performance of the model framework even when using a two-scale hierarchical simulation approach.

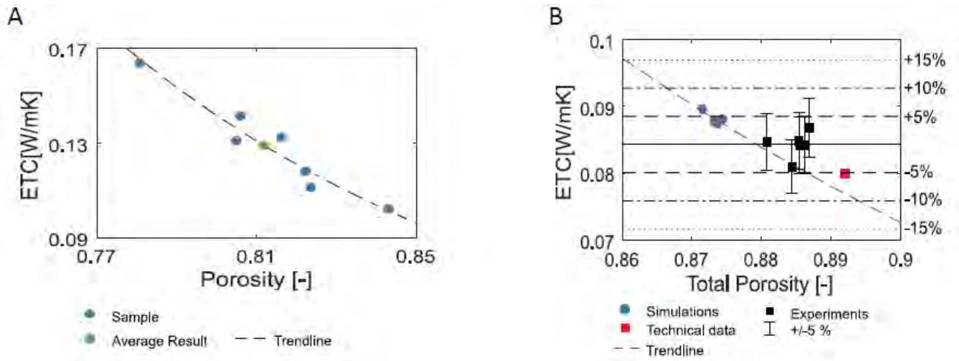

Figure 5. a) Simulation results on the intra-granular scale in the air-dry case, b) Comparison of simulations, experiments and analytical models for the air-dry case of the Reapor material (after Van De Walle et al, 2018).

CONCLUSIONS

The overall goal of this research is to come up with a more accurate description and characterization of the pore structure of building materials. Computer tomography (CT) proofs to be an excellent tool for achieving this objective. Because of its inherent 3D data acquisition, the complete internal structure of the scanned sample can be evaluated at different resolutions. The visualization of the connectivity of the pore network and the detection of additional phases results in an detailed characterization of the building material. The generation of 3D datasets also permits a more quantitative description and calculation of different important parameters such as porosity, hygric properties, heat transfer and spatial variability of these parameters.

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