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Obtaining the spacing factor of microporous concrete using high-resolution Dual Energy X-ray Micro CT

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ABSTRACT

A new technique for three-dimensional classification of concrete is presented along the example of the spacing factor as a proof of concept. The technique is a combination of high-resolution Dual Energy X-ray micro CT combined with a set of subsequent advanced image processing steps to acquire the characteristic parameters used to describe a real porous system. Contrary to the state of the art methods of acquiring one characteristic measure to describe the porous system in a whole, the presented technique can be used to access detailed parameters of a real porous system with a direct and physical adequate correspondent in a three-dimensional volume.

1. Introduction

The performance of composite materials is in many cases directly linked to distribution and structure of their constituents. This holds true for a large range of materials from bimetals over fiber reinforced substances to admixtures. An important field of research is the establishment of a connection between the characteristic material performance and the underlying constituent parameters, demanding workflows to extract these parameters in the first place. The feasibility of each of these workflows is directly connected to the particular state-of-the-art of science and technology, which is the reason, why workarounds have been found in these cases, where the direct assessment of parameters has been impractical or impossible, in many cases leading to approximations and estimations. Here we present one possible workflow to assess the underlying constituent parameters directly along the example of the spacing factor in microporous concrete, as it is a widely used measure and industry standard, however it will be noted, that this workflow is easily adaptable to a big range of other structural problems as will be expanded in the conclusion.

In the example of concrete as a composite material, the characteristics of the system of air voids inside the material have been found to play a dominant role in estimating properties such as permeability or freeze-thaw durability as it is directly linked to strains inside the material arising from freezing water. As no feasible method was existent to directly extract different parameters, such as the size or shape of each single air void, approximations and generalisations have been made to calculate more general descriptive parameters from data, which is more easily acquired. One example is the distance- or spacing factor, that was introduced as a single number to predict the freeze-thaw durability of different kinds of concrete based on their porous system and can be calculated from data gained by measuring traversal lines on polished thin-sections or surfaces. There is an enormous range of different theoretical approaches describing different characteristics with different approximations using advanced stereological descriptions and statistics, including uncertainty estimations and statistics qualifications covering measures like paste content, void-void proximity or nearest neighbour [1]. All these approaches share the paradigm, that the underlying characteristics are important to describe the behaviour of the composite material as a whole but also that arriving at these characteristics is only possible by lower-dimensional approximations. Dual Energy X-ray Micro CT is a technique delivering high resolution and high contrast three dimensional voxel[1] datasets of samples. Especially in concrete, where different phases are only distinguishable by their density rather than their

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[1] A voxel is the three-dimensional analogon to a pixel.

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chemical composition, DE micro CT has superior contrast to mono-energetic CT. The enhanced contrast can then be used to successfully segment even complex multiphase systems with similar chemical composition. In concrete, these segmentations together with image analysis steps can be used to directly extract the aforementioned characteristics. It will be shown how even complex definitions such as the spacing factor can be derived from this direct measurements but the technique presented is not limited to this application and, by further adjustment, might provide answers to complex questions about the pore size distribution or diffusion lengths in a real porous system.

1.1. Theoretical background

An ideal porous system is a spatial arrangement of spherical pores of one phase embedded in a homogeneous environment. All of these pores have the same radius r_{ideal}, surface F_{ideal}, volume V_{ideal} and a sphericity ψ of 1, which is defined as

$$\Psi = \frac{\pi^{1/3} \cdot (6V)^{2/3}}{F} \tag{1}$$

and is 1 for an ideal sphere. Each pore is situated in the middle of a cube with uniform edge length a. The maximum distance between two pores is in the direction of the cube diagonal. The points with the maximum distance from the surface of the pore therefore are the vertices at the 8 corners of the cube. The spacing factor L_{ideal} therefore is the half diagonal length, minus the radius of the pore

$$L_{ideal} = \frac{a}{2} \cdot \sqrt{3} - r_{ideal}. \tag{2}$$

Concrete is far away from being an ideal porous system as the air voids are not perfectly spherical and randomly distributed regarding their center and size. Furthermore the environment usually is very inhomogeneous. As the calculation of a spacing factor for such a system is non-trivial Powers presented the first widely accepted approach to calculate the spacing factor in [2]

$$\bar{L} = \frac{p}{\alpha A} \qquad \text{for} \qquad \frac{p}{A} \leq 4.342 \tag{3}$$

and

$$\bar{L} = \frac{3}{\alpha}\left[1.4\left(\frac{p}{A}+1\right)^{\frac{1}{3}} - 1\right] \qquad \text{for} \qquad \frac{p}{A} > 4.342, \tag{4}$$

with the volume fraction of paste p and air voids A and the specific surface α of the air voids. The proposed spacing factor $\bar{L}$ already is comparable to a mean over the whole porous system due to the assumptions made in its derivation. This is why Attiogbe states that "the actual air-void spacing in the hardened concrete could be much less than that indicated by the calculated spacing factor, resulting in a greater freeze-thaw protection than can be predicted." [3, p. 174] and therefore proposes a mean spacing factor $\bar{s}$, which should be used for better results. The proposed $\bar{s}$ is based on the idea, that it measures the maximum way water has to travel inside the hardened paste until it reaches an air void. After some geometrical and statistical approximations it follows that $\bar{s}$ can be calculated as

$$\bar{s} = 2f\frac{p^2}{\alpha A}. \tag{5}$$

As f is the fraction of the paste resistant to expansion of freezing water, it often becomes 1 if the whole concrete should be freeze-thaw resistant. It is stated that "current measuring techniques do not allow for the size or spacing of the air voids to be measured[…]" [4, p. 18], this is why the state-of-the-art method to determine the spacing factor, the approximation with the microscopic line-traversal method, is based on this theory.

A reliable measure should have a straightforward physical representation. In the case of the spacing factor this corresponds to the maximum distance, water has to travel inside the hardened paste phase until it reaches an air void. Fig. 1 shows the different possibilities for trajectories of a water droplet inside the paste phase, including the shortest distance to the next air void.

It will be explained in the following, how an accurate representation of this measure can be determined inside the sample volume in three dimensions.

2. Materials and methods

2.1. Sample acquisition

The samples used for the experiment are cores drilled out of the side mountings of a bridge along the german autobahn A96 near the descent to the autobahn A99 west of Munich. The identification plate number of the bridge is 7834525 – BW161 = 3 and can be found at the coordinates 48.118004 N, 11.390365 E. The cylindrical samples with a radius of 50 mm and a height of 80 mm are cut in half and prepared for microscopic measurement according to [5]. From this samples, smaller cylinders with a diameter of 9 mm and a length of approximately 30 mm for the tomography are cut out using a water-cooled hollow drill. Further information about the composition of this samples can be found in Table B.3.

2.2. Experimental procedure

Before extraction of the tomography samples, the half-cylindrical samples were measured for their air void distribution and spacing factor according to [5]. A low energy tomography of each cut-out small cylinder was taken with the versa XRM 500 (Xradia) at

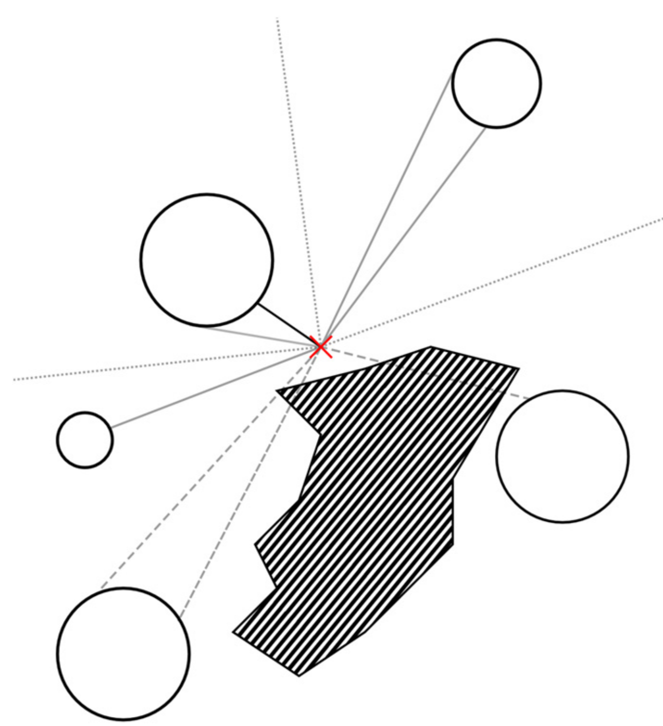

Fig. 1. Schematic drawing of water trajectories in a real porous system. Trajectories of a water droplet (central cross) that do not reach a pore (dotted lines), are blocked by a particle in the aggregate phase (hatched area) or other pores (dashed lines) or directly reach a pore (solid lines). The solid black line shows the path of shortest distance.