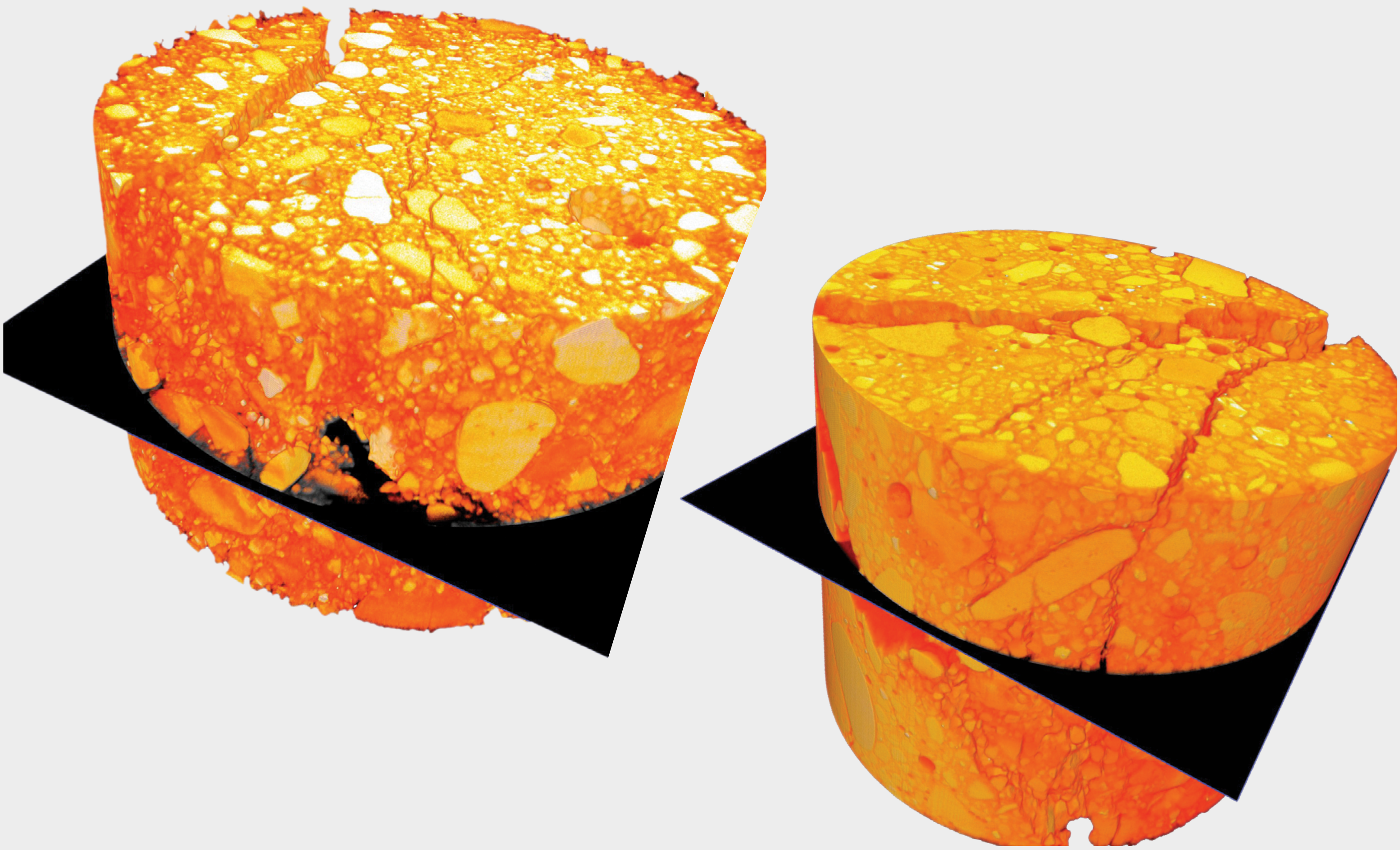

3D Submicron Imaging of Cracking in Building Materials

ZEISS Xradia Versa X-ray Microscopes

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Author: Carl Zeiss X-ray Microscopy, Inc.

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Understanding the fundamentals of cracking in cement-based building materials continues to be a strong area of research and funding in both academia and industry. Early-stage cracking in concrete materials has been estimated to cost the building industry near US$500M annually, with around half of the problem occurring at field construction sites. Additionally, improved understanding of the mechanisms involved in concrete cracking and subsequent failure could conceivably save thousands of lives lost during natural disasters. To address the limitations of existing imaging methods in determining crack mechanisms and crack geometry, ZEISS Xradia Versa 3D X-ray microscopes (XRM) provide non-destructive submicron true spatial resolution for 3D crack morphology imaging. It also enables high resolution *in situ* imaging to quantify fracture evolution during stress and environmental conditions.

Cracking in building materials can be induced by a number of different mechanisms, including lack of moisture or excess heat generation during the early stages of curing, and due to mechanical stress or internal chemical origins (such as rebar corrosion) in longer-term cracking. Due to the large number of crack mechanisms, the highly varying 3D topologies of crack networks are difficult to characterize.

Traditional techniques for understanding the sources and effects of cracking have thus far been limited by resolution and the complexity of the 3D nature of cracking. Low resolution (from 100 µm to several mm) acoustic and coarse 3D X-ray techniques such as micro-computed tomography have provided useful information into macro crack structure. A few high-end conventional micro-CTs provide higher resolution, but on very limited sample sizes. Many other high resolution studies have used optical or SEM imaging of individual slices of the material, an inherently destructive technique that limits the useful information to only 2D surface views.

X-ray Microscopes from ZEISS

The ZEISS Xradia Versa Family provides submicron 3D resolution to capture the complex nature of cracks in relatively large sample sizes. Its unique two-stage magnification system enables high resolution at large working distances (see Tech Note: Resolution of a 3D X-ray Microscope). The system provides the following three key advantages for crack imaging in building materials:

- *Submicron Resolution:* Down to submicron (50 nm) spatial resolution to image emerging hairline fractures and those close to the crack tip;

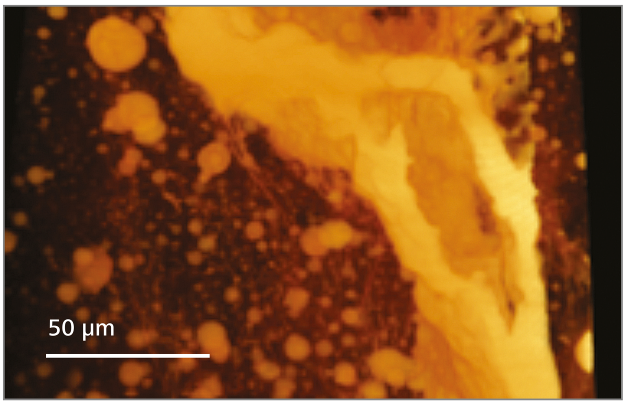

Figure 1 *Inversion of a region of interest in concrete to highlight the cracks and voids.*

- *Superior Contrast:* The system's proprietary PhaseEnhanced™ detectors provide superior contrast to distinguish different phases within building materials. ZEISS Xradia Versa implements propagation phase contrast (see Phase Contrast Tech Note), a technique that highlights fracture interfaces;

- *In situ and 4D Capabilities for Fracture Mechanism Identification:* Because ZEISS Xradia Versa uses dual magnification – optical as well as geometric – it is unhampered by the traditional resolution limitations of projection based systems and is able to maintain high resolution, even at large distances. This enables non-destructive, high resolution imaging of samples within *in situ* chambers. Repeated measurements of crack network evolution under stress and/or environmental conditions are possible, thereby enabling quantification and correlation of cracking within the same sample under varying conditions.

Results

The images to the right provide an example of sub-area imaging within a failed 50 mm concrete specimen. Two scans were performed; one at 20 µm voxel size resolution with 40 mm field of view (FOV) and one at 10 µm voxel resolution with a 20 mm FOV. The 20 µm voxel scan provides a useful overview of the entire crack structure while the 10 µm voxel scan allows for detailed investigation of any sub-region of the sample. By utilizing the unique architecture of ZEISS Xradia Versa and their high resolution detectors we are able to obtain very detailed information about the crack morphology on samples without the need to destructively reduce their size. This is ideal for time-dependent studies where the same sample can be loaded to increasing levels and the same internal region imaged to enable the detailed examination of crack initiation and propagation.

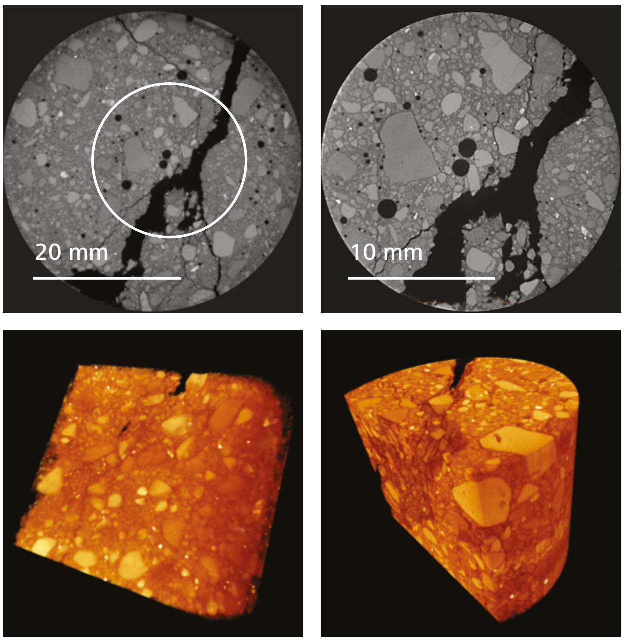

Figure 2A *(Top Row) Various images showing 20 µm voxel resolution (40mm FOV) on the left and 10 µm voxel size (20 mm FOV) on the right. Both scans were taken on the same, intact, 50 mm sample. (Bottom Row) 3D view of same images*

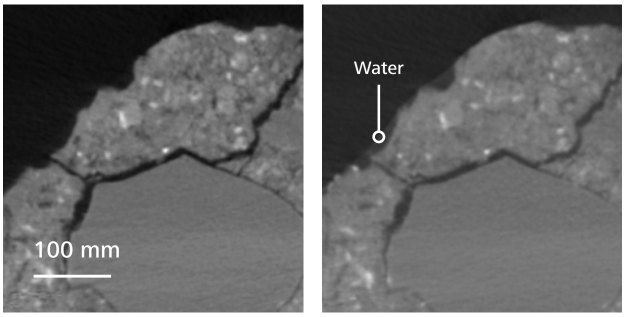

Figure 3 *4D study under environmental conditions. High contrast enables view of wetting effect.*

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[3] NIST Engineering Laboratory (2011). Sustainable, High Performance Infrastructure Materials Program. http://www.nist.gov/el/building_materials/polymeric-materials/shpim.cfm#_ftn2. 'most frequently observed failure mode in the short-term sustainability of concrete being early-age cracking, estimated to cost the U.S. industry $500 M annually.'

Carl Zeiss Microscopy GmbH
07745 Jena, Germany
microscopy@zeiss.com
www.zeiss.com/microscopy