Examination of Damage Processes in Concrete with CT

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Abstract
In order to extend the lifetime of buildings and constructions at the macro scale it is necessary to understand the damage processes of building materials at the micro scale. In particular, durability of reinforced concrete structures is one of the most important requirements for construction planning and restoration of buildings. Therefore degradation mechanisms were reproduced on laboratory specimens. CT (Computed Tomography) is commonly used for non-destructive microstructural defect analysis for recurring tests on concrete specimens. In this work a few examples of CT applications on cementitious materials (including cement paste, mortar and concrete specimens) will be presented.

Firstly, in order to quantify the degradation processes, specimens analysed were damaged by corrosion due to carbonation and due to chloride ingress. Particular focus has been set to the analysis of cracks. An automated crack detection tool, developed by Zuse Institut Berlin (ZIB) and BAM in ZIBAmira, has been applied for quantitative analysis of crack parameters and 3D visualization of cracks. Furthermore the distribution of corrosion products has been evaluated inside the cement matrix and visualized in 3D data sets.

Another important factor for the ageing stability of concrete is the interfacial transition zone (ITZ). The ITZ consists of a layer of cement paste (20 to 40 µm) over every aggregate where porosity is generally increased in comparison with the bulk. This zone could be a preferential zone for transfer of aggressive species. To visualize the ITZ, a small sample of mortar with a diameter of 10mm has been prepared and scanned using the industrial µCT setup at BAM with a spatial resolution of 5µm voxel size. In addition the extracted surface of aggregates could be used for load simulations. We finally show how CT examination of drilled samples taken from building materials in conjunction with laboratory experiments is helpful for further evaluations of damage processes in concrete.

Keywords: X-ray computed tomography, concrete, corrosion, crack detection, 3D visualization

1 Introduction
Concrete is the most commonly used building material worldwide. In 2012 the consumption of concrete in Germany was about 26.7 million tons. Strength and durability of building materials like concrete are influenced by their microstructure. Due to the relatively low tensile strength of concrete, for many constructions steel reinforced concrete is used. One of the primary causes for the limited lifetime of reinforced concrete structures is corrosion. The initial passivation of the steel surface can be altered due to a lower pH created by carbonation reaction, where carbon dioxide from air react with the calcium hydroxide in concrete to form calcium carbonate (pH 8.3). Also the ingress of chloride can depassivate the reinforcement locally. In all cases the occurring corrosion products have a greater volume and will generate additional cracks, which serve as pathways for oxygen, chlorides, carbon dioxide or water. This is a self-reinforcing process. [1] Various electrochemical (EC) and physical techniques have been used to characterize corrosion phenomena. But, especially level of pitting
corrosion can not be quantified by EC. X-ray Computed Tomography (CT) allows the analysis of the internal microstructure in a non-destructive manner. Also the environment (pores, cracks) can be taken into consideration with CT [2] [3].

2 Specimens preparation and measurement

Different cement-based samples with embedded reinforced steel bars (rebar) were produced by CEA (Commissariat à l’énergie atomique et aux énergies alternatives) in Saclay (France) to study the damaging process.

First, as corrosion processes take many years (Fig. 1), reinforced concrete specimens cored on an old structure (aged in seawater during 40 years) have been considered.

Secondly, a reinforced mortar specimen (ring-shape) has been analysed in order to study the influence of cracks on the spreading of corrosion products. For that, a ring-shape mortar sample (Fig. 2) with reinforced steel bar (rebar) was fixed in an apparatus for creating cracks (Fig. 3).

Fig. 1: Core sample of concrete with long-term exposure to seawater.
Fig. 2: Ring-shape mortar sample (left: on scan position, middle: dimension, right: CT - 3D visualization).

Fig. 3: Apparatus for creating cracks on samples.

By manual manipulation of the expansive core (Fig. 3) it is possible to get controlled cracks perpendicular to the exterior perimeter. After this step, samples have been submitted to a carbonation phase in a 50% CO$_2$ chamber. Then, they have been exposed during several weeks to wetting/drying cycles so that carbonation-induced-corrosion has been initiated and propagate.

The third type of sample is cement paste specimens containing steel cylinder (Fig 4). These specimens have been submitted to a drying phase (55% relative humidity) and finally crack.

Finally, mortars specimens have been characterized in order to analyse more precisely the interface between aggregates and cement paste.
All specimens were examined with a 3D µCT scanner at BAM (Fig 5). The scanner is equipped with a 225kV micro focus X-ray tube and a temperature stabilized flat panel detector with 2048 x 2048 pixels. The pixel pitch of the detector was 0.2 mm.

3 Crack detection

Cracks play a major role in corrosion processes inside concrete. If the contrast is high defects are easily recognizable within the homogenous structure of the specimen. Especially large cracks and pores can be separated by using the material threshold, but due to the same grey level pores and cracks couldn’t be distinguished. Figure 6 illustrates this with the cement paste specimens where cracks appeared during the drying of cementitious material.

To separate cracks automatically, the geometry of defects have to be considered, i.e on a small scale cracks can be regarded as thin plates. A tool for automated crack detection was developed by the Zuse Institute Berlin (ZIB) in cooperation with BAM and presented at the ICT-Conference in Wels 2012 [3]. The first application of this tool gives insight into the crack propagation.
Different crack detection methods are available. For thin cracks, template matching is the method with the best results, but computation time is quite long. The so called Hessian-driven percolation is more suitable and able to detect bending and branching cracks (Fig. 7, 8, 9) [4]. The number and shape of detected cracks in all methods depend on the different software parameters. With increasing sensitivity the false discovery rate is increasing, too.

![Fig. 7: Small detail of the ring shape mortar sample: original, template matching and Hessian-driven percolation (from left to right).](image)

![Fig. 8: With template matching detected cracks inside ring shape mortar sample.](image)

![Fig. 9: Detected cracks inside the ring-shaped mortar sample (yellow: cracks, green: rebar).](image)

### 4 Hidden corrosion

#### 4.1 Ongoing corrosion of steel rebars in concrete

To describe ongoing corrosion processes of embedded rebars electrochemical methods are commonly used. The loss in mass of the rebar could be calculated from the electrochemical data by using Faraday’s law. A more accurate result requires the estimation of the rebar surface area, which is involved in the corrosion process. At this point CT is an appropriate method to observe the ongoing corrosion inside a concrete sample at different damage levels non-destructively [3]. For such
examinations two concrete samples with extruded, hot rolled structural steel inside were prepareded
with an artificial crack (Fig. 10) by BAM Division 6.1 Corrosion in Civil Engineering [5].

The sample was measured with the $\mu$CT before and at three points of time during the chloride induced
 corrosion process. For each CT measurement the sample had to be removed from the electrochemical
 measuring device. Registration is necessary to compare the corresponding cross sections on different
damage levels. Therefore the undamaged part of the steel surface, determined by adapted grey level,
could be used as reference for the best fit method in VGStudio MAX. Calculating the difference steel
volume between different damage levels does not require registration and equates the mass loss due to
the corrosion (Fig. 11, 12, 13). Results can be compared with electrochemical and gravimetric
 measurements.

Fig. 10: Concrete sample with embedded rebar and artificial crack

Fig. 11: Vertical cross section of the concrete sample with embedded rebar.
The size of the surface area, which is involved in the corrosion process, could be determined by using the surface models of the differences of the steel volume.

4.2 Distribution of corrosion products
Within a study by BAM and CEA, the spread of corrosion products depending on the distance to the rebar was examined with CT. As precondition for analysing the distribution, the coordinate axis of the data has to be aligned parallel to the rebar axis (Fig. 14).
Analysis of the reconstructed volume was carried out with VGStudio MAX 2.2. As a precondition for evaluation of the spread of corrosion products depending on the distance to the rebar, the coordinate axis has to be aligned parallel to the slice views of the axis of the rebar. To determine the axis of the rebar we fitted a cylinder to the surface of the rebar. Due to the corrosion on parts of the rebar, fit points have been set on the surface of the metal only. Therefore the surface has to be determined by using a local threshold in combination with the common ISO50 mode (called advanced mode in VGStudio MAX). In this process the threshold border between steel and cement matrix has been defined by locally adapted grey values. The axis of this cylinder can be aligned to the slice view, such that the rebar is exactly vertical. The new orientation of the volume data resulted in a temporary coordinate system used for further analysis. In the next step, polygonal cylinders with different diameters have been created to define areas of analysis (Fig. 15), aligned to the rebar orientation. Region of interest (ROI) areas (Fig. 16) were defined according to the areas inside the rebar cylinder and the polygonal cylinders. To get ROIs as thin-walled tubes with equal distances to each other, we subtracted the next smallest cylinder from the outer one. Areas on top and bottom of the specimen, which are not appropriate for analysis (artifacts from Feldkamp reconstruction, partial sample defects), were removed from the ROI areas by the same way. The volume of each cylindrical ring is displayed in the properties window of VGStudio MAX. Due to the surface detection this value represents material only. Voxels of cracks and holes with a similar grey level as voxels outside the object (air) are not included. To get the whole volume of the area to be analyzed the cylindrical ring volume will be evaluated including the grey values of the whole volume. This would also include regions outside the sample if they are included in the circular ROI areas. To get rid of those regions, the external volume has to be cut. The resulting volume of the corrosion products can be extracted from the grey value histogram peak (Fig. 16).
Fig. 16: Greyvalue-based separation of corrosion products (red marked) in one circular ROI area.

Other areas like stones with the same grey values as the corrosion products have to be cut out from the selection before data evaluation. Voxel sized gaps can be corrected by using morphological filters like the Erode/Dilate mode of VGStudio MAX. The size of the corrosion product volume inside a ROI was considered in relation to the ROI material volume. The results can be displayed in a diagram (Fig. 17).

Fig. 17: Results of the CT image analyses.

In 3D CT data recognition of corrosion products inside concrete matrix is difficult. The common size of CT data makes a manual segmentation inefficient or impossible. To improve the possibilities for analysis of structures like corrosion products a new software tool for this requirement will be developed by ZIB and BAM.
5 Aggregates

Aggregates as structural filler in concrete have a great relevance for the strength and for the durability. Its affects also the cement paste properties, particular close to the aggregate surface. Due to the manufacturing process of concrete, it forms a narrow region with deviating density around the aggregate particles, called interfacial transition zone (ITZ). A very small concrete sample with a diameter of 10mm was prepared by CEA to visualize this phenomenon. The achievable resolution is about 5µm voxel size (Fig. 18).

![Fig. 18: Specimen close to the exit window of the X-ray tube to get a high magnification.](image)

Fig. 18: Specimen close to the exit window of the X-ray tube to get a high magnification.

Fig. 19: Halo around the sand grain in a vertical cross section.

Halos with a thickness of about 15 to 25 µm around each sand grain have been interpreted as ITZ between the sand-cement paste interface and the bulk cement paste (Fig. 19). At this high magnification, the halo could also caused by phase-contrast. To exclude this, the part of phase-contrast for this experimental set-up was calculated [6]. It becomes apparent that the influence of phase-contrast can be neglected in this case.
For simulation purposes the degradation mechanisms within concrete, particular migration of chloride ions, and the whole micro structure have to be taken into account. Therefore the positions and shapes of the aggregate particles have to be segmented from the CT images. As a preprocessing step different filter operations such as noise reduction, intensity raising, gap closing and connected aggregates splitting have to be applied. Afterwards aggregates could be segmented and the surface of each grain could be extracted as polygonal surfaces (Fig. 20).

![Segmented aggregates](image)

Fig. 20: Segmented aggregates.

### 6 Conclusion

µCT in combination with appropriate image analyzing software is a powerful tool to support the study on damage processes in concrete samples non-destructively. Contrary to other measurement methods, often describing only one feature, CT provides spatial information about the internal structure, which plays a decisive role in this context. Core samples, which were often used in the field of building material testing, are mostly appropriate for CT examination. The potentialities are limited by the spatial resolution which depends on the sample size. Thin structures like micro cracks and the interfacial transition zone (ITZ) are only recognizable with a combination of small sample size and high resolution micro CT. Automatic crack detection creates key figures, which allow to estimate the influence of cracks in damage processes. Informations about the distribution of corrosion products inside concrete and arrangement of aggregates find their way into the modelling of damage processes, a still ongoing development.

### Acknowledgements

This work was created in the context of a feasibility study realized by BAM on behalf of CEA Saclay and supported by Zuse Institute Berlin (ZIB).
References


