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Monitoring reinforcement corrosion and corrosion-induced cracking by X-ray microcomputed tomography method

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ABSTRACT

X-ray microcomputed tomography (X-ray μCT) method is proposed to trace steel corrosion and corrosion-induced cracking in cement paste. Experimental results show it can track the time-dependent development of steel corrosion and corrosion products, as well as the subsequent initiation and propagation of corrosion-induced cracks. Furthermore, the information of corrosion pits, corrosion products, and corrosion-induced cracks can be clearly obtained from the whole specimen by this novel method. Additionally, SEM/EDS results agree closely with image analyses by X-ray μCT. This method provides a new angle to investigate the reinforcement corrosion process and can help to improve the numerical analysis of corrosion-induced damage in reinforced concrete structures.

1. Introduction

Corrosion of rebar in reinforced concrete is a major deterioration problem of structures, which causes the loss of durability of structures, and thus leads the increase in maintenance and repairs [1–3]. Therefore, the development of technologies and materials to improve the durability of reinforced concrete structures has become an important research subject [4,5]. In recent decades, various simulation models have been developed and are applied to predict the service life of reinforced concrete structures subjected to corrosion damage [4]. These models can be broadly divided into empirical [5], analytical [6,7] and numerical models [8,9]. To validate these models, however, critical information about the real corrosion process is required, such as the point at which corrosion starts, the direction and place where the corrosion products develop and accumulate, and the region where the concrete cover starts cracking [10].

To address these problems, many different techniques have been applied to investigate the corrosion of rebar in concrete [11–15]. In corrosion monitoring, the electrochemical method is the main technique currently in use, for which electrochemical impedance spectroscopy (EIS) is an advanced technique that measures dynamic response over a wide frequency interval [16,17]. Electrochemical noise (EN) is also a valuable method to detect the initiation of steel corrosion in reinforced concrete, the approach of which has little intrusiveness [13,18]. However, by using these electrochemical approaches only indirect statistical information can be provided, other information such as the type of corrosion, extent and distribution of corrosion region is difficult to obtain directly. Thus, so far, investigations regarding mechanisms of rebar corrosion rely on indirect observational methods, such as cutting open samples after evidence of extensive corrosion and external observation of surface crack propagation. These techniques, however, could easily be interfered and/or affected by various human and environmental factors, like testing environment, processing procedure and personal experience, knowledge, and opinion.

X-ray microcomputed tomography (X-ray μCT), which has been widely used in medicine and material science [19], is a promised technology for directly obtaining quantitative information about reinforcement corrosion. Based on multiple cross-sectional X-ray scans, X-ray μCT can be applied non-destructively to study and reconstruct 3D internal structures. In order to acquire a comprehensive spatial result, X-ray radiographs are documented at different angles. Application of X-ray μCT has been demonstrated in the characterization study of cementitious materials, such as pore structure characterization, sulfate attack, and diffusivity of cracked concrete [20–25]. Used in related investigations on steel corrosion, X-ray μCT allows for real-time, in-situ 3D characterization and monitoring of reinforcement corrosion, subsequent initiation and propagation of corrosion-induced cracks, and the time-dependent corrosion process of steel reinforcement. Furthermore, the technique provides a platform for real-time monitoring without interfering with the chemistry or morphology of the embedded steel, while offering 3D-imagery for comprehensive analysis. Recently, the similar techniques have been developed for investigating the

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reinforcement corrosion process in concrete [1,11,26]. However, these works cannot be applied to compressively monitor the reinforcement corrosion in some extant due to the limitation of either the low resolution of the X-ray camera-pixel size or the lack of full three-dimensional (3D) information. Therefore, the full three-dimensional information with high resolution is crucial for deeper understanding the corrosion process of reinforcement in concrete.

This paper focuses on the application of the non-destructive test method, X-ray μCT, to achieve a comprehensive monitor of in-situ steel corrosion in cement and its induced damages in specimen cover via high-resolution 3D reconstruction. Here, the X-ray μCT method is applied to track the time-dependent development of steel corrosion and corrosion products, as well as the subsequent initiation and propagation of corrosion-induced cracks. By using this technique, the number and location of identified targets (e.g., corrosion products and corrosion-induced cracks) are collected and analyzed by using an image analysis tool. In addition, scanning electron microscopy (SEM) and energy dispersive spectrometry (EDS) are used to morphologically and chemically analyze the corrosion results. Finally, the mass loss of steel, obtained by X-ray μCT method, is compared with the results measured by using the Faraday's law and gravimetric methods.

2. Experimental approach

In order to test the applicability of the X-ray micro computed tomography (X-ray μCT) method to monitor the development of corrosion products and cracking behavior in cementitious materials, reinforced cement paste samples were tested under accelerated corrosion conditions. The materials and testing methods are described below.

2.1. Specimen preparation

The cement specimens were cast as shown in Fig. 1, where each specimen was formed in a cement block with dimensions of Φ10 × 10 mm and one embedded carbon steel rod, 2 mm in diameter. The thickness of the cement cover is 4 mm. Following the standard mortar specimen fabrication procedure, the fresh mix was cast into molds, each having a centered carbon steel rod. The specimens were then sealed and placed for 24 h in a curing chamber (95 ± 5% RH, 20 ± 2 °C). After 24 h, the specimens were de-molded and placed in the curing chamber for another 28 days under the same environmental conditions. Note that rubberized fabric was used to prevent the corrosion of external steel during the curing and testing procedures.

2.2. Testing procedures

The basic testing procedure is divided into two parts: accelerated corrosion test and X-ray μCT test. The X-ray μCT test was applied after each accelerated corrosion test, in which water applied to the surface of specimens was rapidly desiccated before specimens are placed in the X-ray μCT instrument.

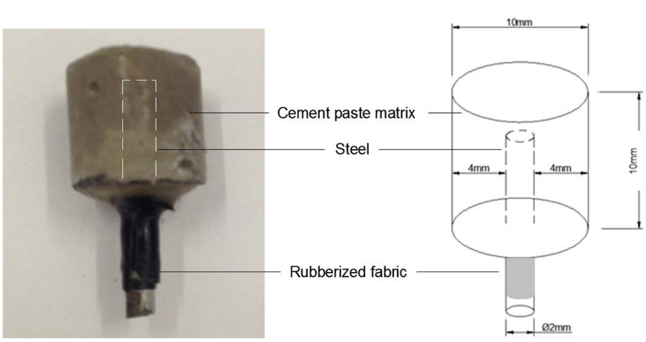

Fig. 1. Schematic presentation of specimens.

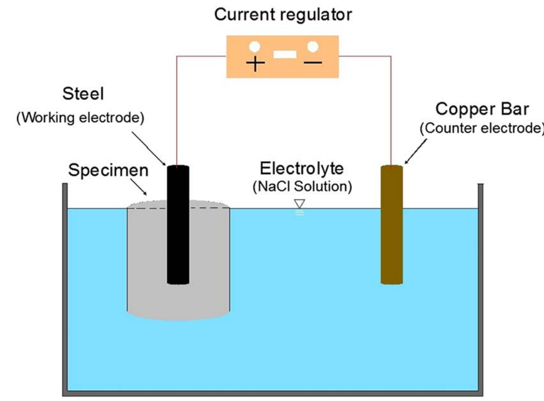

Fig. 2. Schematic illustration of accelerated corrosion procedure.

2.2.1. Accelerated corrosion

To accelerate corrosion of the steel, galvanostatic corrosion was applied, for which the equipment consisted of the reinforced cement paste specimen, a copper bar and a current regulator (see Fig. 2). Electrical connection between the working (steel) and counter electrodes (copper bar) was realized by placing the cement paste specimen in an electrolyte solution with 3.5 wt% NaCl. During the accelerated test, the applied current density was 132 mA/cm^2, which was applied in five runs of 460-s intervals. It should be noted that such a current density certainly exceeds natural conditions. While a relatively high current was applied to induce corrosion to test the applicability of measurement technique, acceleration of corrosion would not be expected to alter the results of corrosion under natural corrosion conditions.

2.2.2. X-ray microcomputed tomography (X-ray μCT) technique

Shenzhen University (China) provided access to their X-ray μCT facility (XRadia Micro XCT-400) for these experiments. The X-ray μCT system comprises a microfocus X-ray emitter, a rotation stage that allows for 360° imaging, an image intensifier detector with three multiple charge-coupled device (CCD) cameras and an image processing unit (see Fig. 3). The X-ray tube used in this study was equipped with a small focal spot (microfocus X-ray-tube) and optical magnification technique enabled a high resolution. By means of X-ray μCT, the resolution of volumetric picture elements (voxels) was extended to one micron. Consequently, the structure of multiphase particles with a size on the order of 10 μm can be reconstructed in 3D. In addition, the working distances between source, sample and detector are typically around 100 mm in this system, which means that full tomography can be achieved even for larger samples.

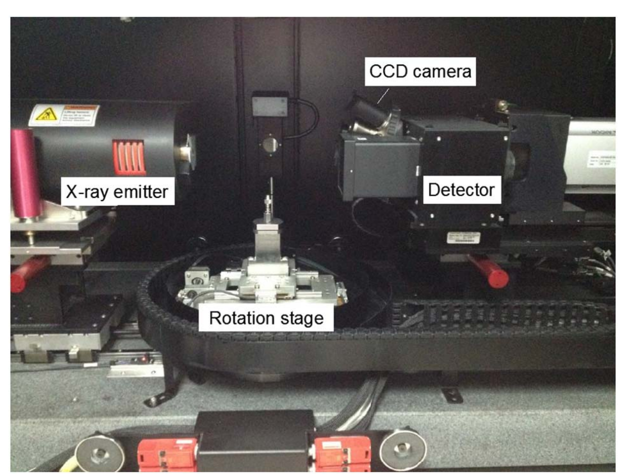

Fig. 3. Internal features of XRadia Micro XCT-400.

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