



Three-dimensional characterization of steel corrosion embedded in cement paste



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HIGHLIGHTS

- μ CT was used to investigate steel corrosion embedded in cement paste.
- Corrosion was initiated at a certain direction by the formation of pits.
- More corrosion accumulated at the direction where penetrating cracks exist.

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ABSTRACT

In this research, a micro X-ray computed tomography (μ CT) technique was used to investigate the distribution of steel corrosion embedded in cement paste non-destructively. An electrochemical method was used to accelerate the corrosion of steels for two designed levels of corrosion (2% and 18%). For μ CT observations, two camera lenses (0.4 \times and 4 \times camera lenses) were used to globally and locally investigate the tomography of un-corroded steels, corrosion products as well as cracks. The factors affecting the corrosion distribution, such as the immersion depth in NaCl electrolyte as well as the arrangement of cathode position were also investigated. Test results showed that corrosion started at a certain direction by forming pits. For both corrosion levels, the distribution of corrosion products is not significantly related to the position of cathode electrode but related to the distribution of cracks. More corrosion products accumulated at the steel surface where penetrating cracks occurred; whereas in the occluded cracks, the corrosion product was insignificant. Furthermore, the actual corrosion level was found to be related to the immersion depth in NaCl electrolyte. i.e., with the increase in the depth of immersion, the steel corrosion level increased.

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1. Introduction

Reinforced concrete structure is one of the most widely used forms of construction with various advantages such as low cost, long service life and ease of materials availability. However, deteriorations (such as steel corrosion and cracking in concrete) caused by materials degradation and aggressive environments will lead to functional and economic loss [1]. In order to reduce the repair costs, a number of analytical and numerical models have been proposed to assess the mechanical consequences of the corrosion process [2–4]. However, due to lack of crucial information, the difference between the model predictions and experimental

results remain. For example, most models assume a uniform layer of corrosion products around the steel/concrete interface, which is not accurate enough for characterizing the chloride-induced corrosion of steel reinforcement [5]. Thus, a full understanding of the corrosion propagation in protecting layer of cement based composite is required for the development of models.

In conventional research, the corrosion of steel and associated cracking behavior is observed through destructive methods, for example, cut, open, and polished samples are required for scanning electron microscope [6] or optical microscope [7] investigation or direct measurement [8]. Although, indirect methods give valuable insight into the extent of corrosion; however, when observing an open sample, extra cracks and artifact might be introduced during sample preparation [9].

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Recently, initiatives have been taken for monitoring reinforcement corrosion and corrosion-induced cracking using non-destructive methods such as acoustic emission [10] and neutron tomography [11], etc. However, their observation is limited to meso or macro scales. Another non-destructive technique, namely X-ray micro-computed tomography (μ CT), has also been used recently for evaluating concrete fracture and corrosion processes at microns level [12–15]. This technique has been used successfully for monitoring of porosity, corrosion, and subsequent cracking. For example, Beck et al. [12] studied the development of average mass loss of reinforcement with time. However, the crack pattern in cover was not monitored. Itty et al. [14] used the above mentioned technique to monitor the three-dimensional (3D) distribution of corrosion of carbon steel and stainless steel wrapped cement mortar. However, the discussion about the relationship between the distribution of corrosion products and cracks was not very detailed. The distribution of corrosion products and cracks at a certain plane was investigated by Šavija and Michel et al. [13,15]. However, their work did not provide much 3D information. Hence, up to now, the 3D distribution of corrosion products and cracks, and the relationship between them has not yet been systematically reported.

In the present research, a μ CT technique was used to investigate the steel corrosion embedded in cement paste in order to fully understand the corrosion mechanism and establish accurate models for predicting the development of corrosion. For this purpose, an electrochemical method was used to accelerate the corrosion of steels. The factors that could affect the corrosion distribution, such as the immersion depth in NaCl electrolyte, arrangement of cathode position, and 3D distribution of cracks, were also investigated.

2. Experimental details

2.1. Materials and sample preparation

The hot-rolled steel sample having dimensions of 3 mm diameter and 35 mm length was embedded in cement paste along the central axis of the mould as shown in Fig. 1. The cement paste, which was used as a protective layer for steel, was produced from PII 42.5 Portland cement (Yuexiu cement factory, Guangzhou,

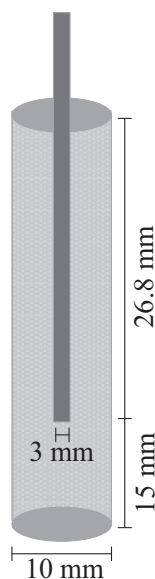


Fig. 1. Schematic view of specimen with average dimensions for μ CT.

Table 1
Chemical composition of cement (mass fraction, %).

Oxide	Mass fraction (%)
SiO ₂	21.20
Al ₂ O ₃	5.40
Fe ₂ O ₃	5.03
CaO	64.84
MgO	1.45
SO ₃	1.02
Loss on ignition (LOI)	1.06

Table 2

Geometric dimensions of steel embedded in cement paste. *D*: Diameter, *l*: Length, *S*: Contact area.

Specimen	<i>D</i> (mm)	<i>l</i> (mm)	<i>S</i> (mm ²)
S1	3.00	28.05	264.37
S2		26.55	250.23
S3		25.96	244.67
S4		28.21	265.87

China). The chemical composition of cement is shown in Table 1. The cement was mixed with deionized water (water-to-cement ratio of 0.4) at a high speed for 2 min. The mixture was then poured into cylindrical moulds (diameter: 10 mm, length: 42 mm) containing steel bar and subsequently the sealed specimen was kept at room temperature for 3 days. Thereafter, the sample was demoulded and placed for 28 days in a curing chamber at 25 °C and relative humidity of 90%. During the curing process, the exposed part of steel was protected by epoxy so as to avoid possible corrosion.

In total, four specimens (S1–S4) were prepared. The length of the embedded part of steel in cement paste was approximately 26.8 mm while the distance between the end of steel and the bottom of the mould was approximately 15 mm (Fig. 1). However, due to deviation in the preparation process, the embedded part of the four steels differed slightly in length as shown in Table 2.

2.2. Galvanostatic corrosion of steel

After 28 days of curing, an electrochemical method was used to accelerate the corrosion of steel as shown in Fig. 2. The specimens were immersed in solution containing 3.5% per mass of sodium chloride up to a depth of 20 mm (container size: 50 × 50 × 40 mm³). The steel was connected to the positive electrode as anode while copper strip (length, width, and thickness of approximately 27, 2, and 0.15 mm, respectively) affixed to the surface of the specimen was connected to the negative electrode as a cathode, forming an electric circuit. Galvanostatic was applied

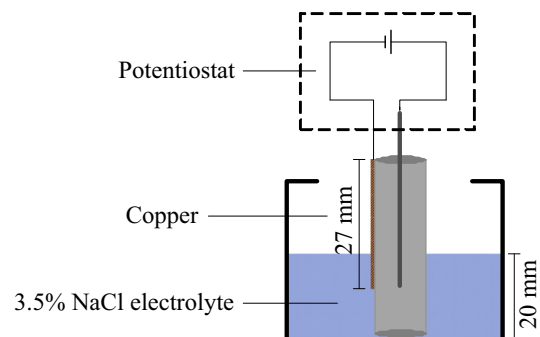


Fig. 2. Electrochemical setup used for galvanostatic corrosion.

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