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Non-uniform corrosion of steel in mortar induced by impressed current method: An experimental and numerical investigation

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HIGHLIGHTS

- A new method for inducing non-uniform corrosion of steel in mortar is deigned.
- Rust distribution pattern by the proposed method is similar to natural corrosion.
- FEM models was established to semi-quantitatively study the experimental parameters.

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ABSTRACT

In this work, a new experimental method was proposed to rapidly induce non-uniform distribution of rust layers around steel bars in mortar and concrete. The proposed method is based on the impressed current method with short testing duration, but capable of inducing morphologies of rust distribution closer to those observed in natural corrosion environments than other existing methods. X-ray microtomography with image analysis techniques was implemented to quantify the rust formation and propagation in the proposed setups. A finite element model to systematically and semi-quantitatively investigate several experimental parameters (e.g., the distance between anode and cathode, the anode-to-cathode area ratio) was established and verified by a series of independent experimental programs.

1. Introduction

Chloride-induced corrosion of steel in reinforced concrete (RC) structures has been one of the most common deterioration mechanisms globally [1–3]. The corrosion of rebar in concrete can result in the formation of longitudinal cracks, peeling-off of concrete cover, degradation of steel-concrete bonding, as well as reduction of structural bearing capacity and ductility [4–6]. Due to the significance of this issue, a tremendous amount of work has been done over decades regarding the lifetime prediction of RC structures exposed to chloride-induced steel corrosion [3,7–15]. According to the previous studies, the corrosion propagation of steel in concrete after corrosion initiation is very important to the accurate assessment of RC structures and prediction of service life [4,16–20]. Many investigations have been conducted, including, the crack shapes and rust distribution patterns around the corroded rebar [21–26], the prediction of concrete cover cracking initiation time [27–31], the relationship between corrosion-induced crack widths and rust formation [32–38], among others.

There are primarily three laboratory techniques for studying the corrosion characteristics of rebar in RC structures in literature, namely, natural exposure [13,39], accelerated corrosion using artificial climate environments [24,40,41], accelerated corrosion using impressed current method [24,37,38,41,42]. A comparative study of different accelerated corrosion techniques in RC beams concluded that natural corrosion and accelerated corrosion using artificial climate environments show similar corrosion characteristics [24]. In particular, at the early stage, the side of rebar closer to concrete cover corrodes first, showing a non-uniform corrosion pattern. While at a later stage after the cover cracks, the corrosion pattern tends to become uniform. In contrast, the corrosion pattern of rebar in concrete accelerated by impressed current method maintains a uniform distribution. As such, it can be criticized that the analysis of corroded RC members based on impressed current method may not be representative of the in-service members

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[43,44]. For example, at the same level of corrosion, the uniform corrosion-induced tensile stress in the concrete cover is considerably smaller than the non-uniform corrosion induced by other methods [18,21]. In addition, the failure modes of RC members with uniform and non-uniform corrosion are different, which would result in an overestimation of the structural capacity and safety [45,46]. Nevertheless, it is clear that the impressed current method has some advantages over natural corrosion and artificial climate environment method, including short acceleration duration and high repeatability.

This study attempts to propose a new experimental method to induce non-uniform corrosion in mortar and concrete with a similar rust distribution pattern as that found in natural corrosion environment, in particular, the Gaussian-type distribution. The proposed method, combined with numerical modeling, can be easily extended to design the corrosion pattern in concrete. The proposed method preserves the advantages of the traditional impressed current method, which would be alternative to the other corrosion acceleration methods, particularly when studying the concrete cover cracking behavior in RC members due to non-uniform corrosion.

2. Experimental program

2.1. Materials

Ordinary Portland cement (OPC) mortar specimens were prepared. The OPC was an ASTM Type I cement prepared by grinding clinker with 5% (by mass) gypsum. The equivalent alkali content (denoted as $Na_2O + 0.658K_2O$) in OPC was less than 0.60% by mass. The fine aggregates were silica sand with a specific gravity of 2.61 and particle size ranging from 150 to 300 µm. The water was from tap water. In addition, polycarboxylate superplasticizer was used to ensure workability and consistency of the mortar. The mortar specimens were prepared by mixing OPC, water, superplasticizer, and sand in a ratio of 1:0.35:1.5:0.004 (kg/m^3). The steels embedded in mortar specimens were hot-rolled plain bars with a diameter of 6 mm and chemical composition in Table 1. The proposed testing method can be easily extended to corrugated black steel or other reinforcing steel bars. An ASTM 304 stainless wire with a diameter of 0.5 mm was used as the auxiliary electrode during corrosion acceleration as elaborated later. In addition, 3.5% NaCl with respect to the mass of cement paste was added during the mortar mixing in order to initiate steel corrosion.

Table 1
Chemical composition (mass %, max. content).

	C	Si	Mn	P	S
Rebar	0.25	0.55	1.5	0.045	0.05

2.2. Specimen preparation

The configuration of the designed mortar specimens is shown in Fig. 1. A series of customized polymethyl methacrylate molds were designed and manufactured to prepare the specimens. The purpose of implementing cylindrical shape specimens was to ensure that the mortar cover thickness was uniform around the circumference of steel. For each specimen, it was basically a cylinder with a height of 20 mm and a diameter of 20 mm. The round steel was embedded in the center of the mortar cylinder and the stainless wire was 3 mm away from the steel. The reason of using plain steel bar instead of the traditional corrugated black steel is to simplify the rust thickness quantification. However, it should be noted that the applicability and effectiveness of the proposed method are independent of the geometry and size of the specimens as well as the morphology of bar surface. The mortar cover thickness was 7 mm in all directions. The reason for preparing such small geometry specimens was due to the requirements by the implemented X-ray Micro Computed Tomography equipment as mentioned later. After casting, the specimens were cured in an environmental chamber with 75 ± 5% relative humidity and 20 ± 2 °C for 28 days.

2.3. Corrosion acceleration method

After curing, the corrosion propagation of steel embedded in the mortar was accelerated by the impressed current method as elaborated later. It should be noted that due to the internal addition of sodium chloride in the mortar, it was believed that the steel corrosion has initiated with destroyed passive film. During the corrosion acceleration, the steel was connected to the anode while the

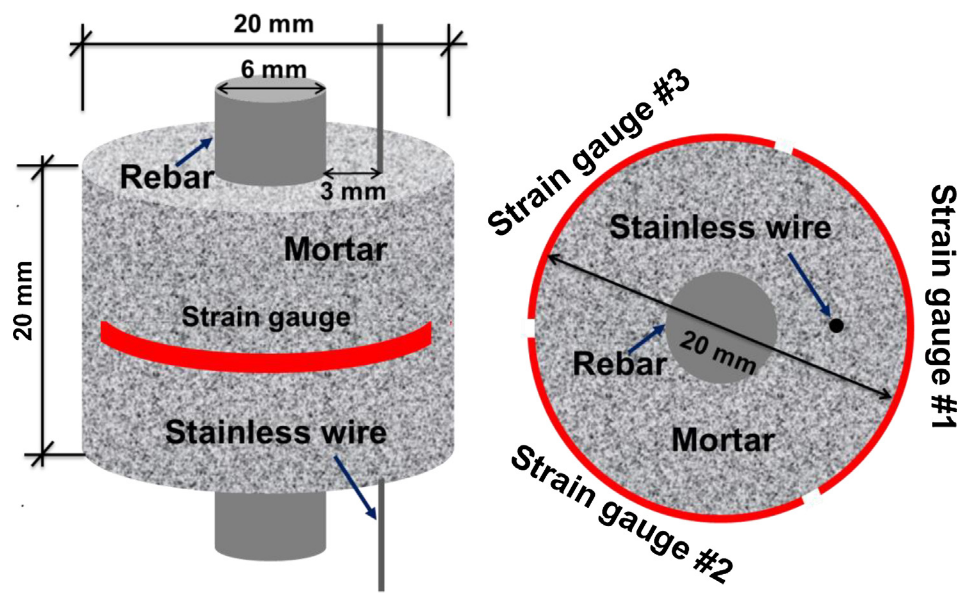

Fig. 1. Configuration of the designed mortar specimens for steel corrosion acceleration (left) Front view; (right) Top view.