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Non-uniform distribution of a corrosion layer at a steel/concrete interface described by a Gaussian model

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ABSTRACT

Corrosion layers at the steel/concrete interfaces of two reinforced concrete specimens subjected to chloride ion ingress were observed and measured by SEM. A Gaussian function was used to model the distribution of the non-uniform corrosion. The physical meaning of the parameters in the Gaussian model is confirmed mathematically and the relationships among these parameters are discussed. The locations of the corrosion peaks along the rebar perimeter are also discussed. When the number of cracks at the steel/concrete interface becomes two or more, the corrosion layer has the same quantity of corrosion peaks. A multi-peak Gaussian model is proposed to describe this multiple corrosion peak situation.

1. Introduction

The corrosion of steel has been identified as the major cause of deterioration in reinforced concrete structures [1,2]. The corrosion of steel produces pressure on the surrounding concrete because the volume of corrosion product is 2–6 times the volume of the original steel [3–5]. Aggressive agents reach the reinforcement directly from these corrosion-induced cracks and accelerate the corrosion process, leading to serious damage [6–8]. To accurately predict the time taken to reach the limiting state of the cracking, concrete cover is not only important for the durability of reinforced concrete structures but also provides the scientific basis for structural maintenance. Therefore, the development of a concrete cracking model for reinforcement corrosion has received substantial attention from both scientists and practicing engineers.

Analytical models [1,6,9–17] usually assume a uniform expansion of corrosion products around the rebar circumference. As a previous study showed [18], this assumption is made primarily for two reasons. The first is that it significantly simplifies the modeling process, especially when formulating analytical and finite-difference based solution schemes. The second is that currently there is an absence of reliable information with which to characterize the actual non-uniform formation and expansion of corrosion products from the rebar surface. Because the scenarios of uniform or non-uniform corrosion of reinforcement obviously have different effects on predicting the time to corrosion-induced cracking [18–22] and the non-uniform corrosion around the rebar perimeter is the real situation, the variability of the thickness of the corrosion layer deposited on the circumference of the steel bar must also be determined when formulating a mathematical model.

Several models to describe the non-uniform corrosion of the steel bar have been made over the past several years: a semi-elliptical rust model by Yuan [19], linear models by B.S. Jang [20], a dual oval rust model by Liu [21] and Gaussian models by the authors [18,22]. The authors' previous works demonstrated that a Gaussian model is the most reliable for comparing both Yuan's and the authors' tested results [22]. The authors also define the physical meaning of the parameters in the Gaussian model. However, previous works have lacked a discussion of the relation among these parameters and their functions in practical situations. Furthermore, the testing specimens in the previous study are limited.

Following up on the authors' previous work [18,22], this paper mathematically confirmed the physical meaning of the parameters of the Gaussian model and also investigates the relationships among these parameters by measuring the thickness of the non-uniform corrosion layer around the perimeter of the steel bar in two different types of specimens. The location of the corrosion peak along the rebar perimeter is also discussed based on which multi-peak Gaussian model is proposed to describe the multiple corrosion peak situations.

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Table 1
Information of the two concrete specimens.

Specimen number	Quantity	Compressive strength at 28 day age (MPa)	Ratio of water/binder	Mixture composition (kg/m^3)			
				Cement	Sand	Aggregate	Water
TC30	1	38.2	0.56	351	650	1157	195
AC40	1	49.9	0.44	439	571	1161	195

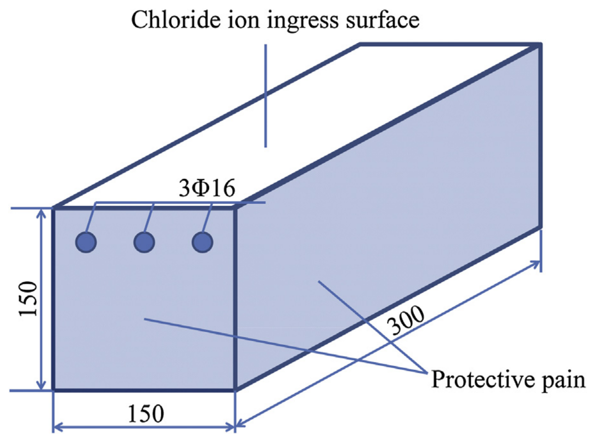

Fig 1. Schematic of the reinforced concrete specimen (dimensions are in mm).

2. Experimental program

2.1. Specimens

Two specimens, which were subject to different chloride ingression environment, are used for observation and analysis in this study, i.e. TC30 and AC40. Both of these two specimens have cracked. The size of these two concrete specimens is 150 mm × 150 mm × 300 mm, as shown in Fig. 1. Each specimen contained three deformed carbon steel bars with a nominal number of 16 mm. The information of these two specimens is reported in Table 1.

To ensure the unidirectional diffusion of chloride ions when specimens are in the deterioration process, the side and bottom surfaces of each panel were surface treated with protective paint (which is indicated by the blue shade in Fig. 1) to ensure that chloride predominantly penetrated the top cover, with minimal penetration of the other faces of the panel.

2.2. Curing and exposure history

The flow chart of the curing and exposure history of two specimens are illustrated in Fig. 2 and Table 2, also stated in detail as follows.

2.2.1. Specimen TC30

Specimen TC30 was first soaked in a 5 wt.% sodium chloride solution at various temperatures. Each temperature-cycle included 24 days, including 4 days in 36 °C, 8 days in 46 °C, 4 days in 34 °C and 8 days in 36 °C, as listed in Table 2. This specimen underwent 20 cycles in total. The specimen was then subjected to the wetting and drying cycles. Each wetting-and-drying- cycle lasted for 7 days and consisted of soaking the blocks with a 3.53 wt.% sodium chloride solution for 3 days and subsequently allowing it to dry in a lab environment for 4 days.

2.2.2. Specimen AC40

Specimen AC40 was placed in a salt mist chamber for 111 days. Each day, the specimen was subjected to 5 wt.% sodium chloride mist for 21 h, with 1.0–2.0 mL/(80 cm^{2}h) settlement of the mist, a temperature of 35 ± 2 °C and 100% RH. The specimen was then air-dried for 3 h at room temperature and 85% RH. The second exposure stage was the same for specimen TC30, i.e., 7-day wetting and drying cycles.

2.3. Sample preparation

The selected panel was cast into a low-viscosity epoxy resin to minimize any artificial damage that may have occurred during the sample preparation process for microscopy. The epoxy was allowed to harden for several days and then was carefully cut by a Φ355-mm concrete cutting machine to extract the corner and middle rebar while keeping the surrounding concrete intact, as shown in Fig. 3. Cutting was performed at least 15 mm away from the rebar to minimize any disturbance of the rebar-concrete interface. The cut

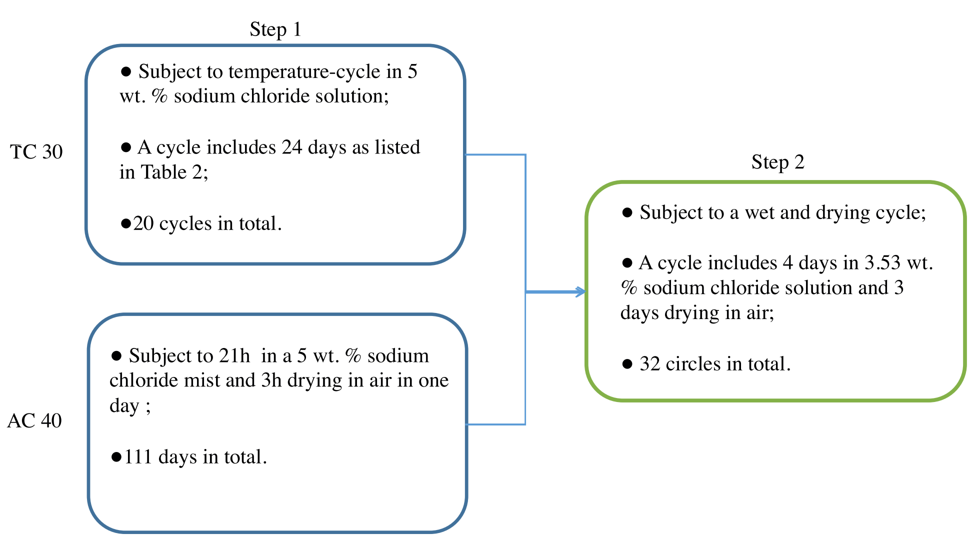

Fig. 2. The flow chart of the curing and exposure history.