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The vertical Non-uniform corrosion of Reinforced concrete exposed to the marine environments

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HIGHLIGHTS

- The vertical non-uniform corrosion of reinforcement bar in concrete was caused by the difference of oxygen concentration, moisture content, free chloride content and pH value in vertical direction.
- Carbonation mechanism of concrete in the marine environment: the carbonation was a metathesis reaction between the bicarbonate ion (HCO_3^-) of seawater and the alkaline hydration products of concrete.
- The macroscopic non-uniform corrosion of reinforcement bar in the marine environment was galvanic corrosion.

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ABSTRACT

Reinforced concrete (RC) structures usually are exposed to a wide variety of combined actions, which may cause various damages to the structures. The main objective of this study is to investigate the vertical non-uniform corrosion of reinforcement bar in concrete that was exposed to the marine environments. The concrete embedding rebar electrodes array (CRA) was designed and made based on the wire beam electrode (WBE). To simulate the submerged, tidal and splash marine environments, the marine environment simulation equipment (MESE) was set up. Electrochemical behaviors of rebar electrodes were characterized using the WBE method, linear polarization (LP) technique and electrochemical impedance spectroscopy (EIS). To monitor the carbonation and chloride ion penetration of concrete, the pH and chloride ion profiles of the concretes were analyzed. The vertical non-uniform corrosion of rebars was caused by the difference of oxygen concentration, moisture content, free chloride content and pH value in vertical direction. The macroscopic galvanic corrosion between the splash zone rebars and the tidal zone rebars was inhibited and the galvanic corrosion between the adjacent rebars was promoted by the high resistivity of the splash concrete. The concrete carbonation was a metathesis reaction between the bicarbonate ion (HCO_3^-) of seawater and the alkaline hydration products of concrete in the marine environments.

1. Introduction

The corrosion of reinforcement steel has become one of the major causes of structure deterioration for the concrete facilities exposed to marine environments [1,2]. The ingress of chloride ions through the concrete pore network was believed to be one of the most common causes of rebar corrosion in the coastal areas [3]. Considering the location of structural elements in relation to seawater level, five exposure conditions could be introduced including atmospheric, splash, tidal, submerged and soil zones. The mechanism of chloride penetration into concrete is different in each of these zones and is influenced by environmental conditions [4]. The chloride penetration may occur either by diffusion from water-saturated concrete or due to absorption/desorption process throughout wet/dry cycle exposure [3]. Therefore, the corrosion of reinforcement steel is different in each of these marine zones and is influenced by the different distribution of chloride ions in the concrete.

Concrete is a porous material that may react with the surrounded medium. Especially, the carbon dioxide generates the

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carbonation of concrete and leads to the alteration of chemical properties (pH decrease). Moreover, in carbonated concrete, the rebars does no longer remain in its passive state and high corrosion rates can be observed [4]. Tuutti's diagram schematizes the time evolution of the steel/concrete interface with the passive and active periods [5].

Only if enough amount of oxygen is available in vicinity of corroding reinforcement bar in concrete construction, the environmental loadings (such as chloride, carbonation, temperature,) can cause corrosion [6]. Many researchers have investigated the effect of oxygen on corrosion of RC construction [7,8]. Two phases of oxygen existing in concrete are considered: gaseous oxygen and oxygen dissolved in pore water. The gaseous oxygen can move through water-unsaturated pores, whereas dissolved oxygen is transported within pore liquid water. The saturation degree of the concrete and the diffusion properties of oxygen are key parameters to assess the corrosion rates of reinforcement bar. Huet [4] evaluated the whole cathodic process and oxygen diffusion as a function of the water saturation degree of the concrete, considering a continuous evolution of Sr with environmental relative humidity.

Sr $\in$ {1.0; 0.9}: cathodic reaction is under diffusion control,
Sr$\approx$0.9: cathodic reaction is still under diffusion control, but oxygen diffusion rate is high enough to sustain reduction rates in the order of 10 μA cm^{-2},
Sr $\in${0.9; 0.8}: cathodic reaction is under mixed reaction and diffusion control,
Sr less than 0.8: cathodic reaction is under reaction control. Resistivity of the cementitious material has also to be taken into account.

The corrosion of reinforcement bar might be influenced by the chloride penetration, carbonation and oxygen diffusion of concrete in different marine zones. Therefore, this work aims at the vertical non-uniform corrosion of reinforcement bar in concrete that was exposed to the marine environments. The potential and current distributions of reinforcement bar were characterized by the wire beam electrode (WBE) method. Corrosion rates of reinforcement bar were monitored on a regular basis by the DC linear polarization resistance (LPR) method. In addition, the pH and chloride ion profiles of the concretes subjected to the different marine environments were analyzed.

2. Experimental program

2.1. Materials and specimens

The reinforcement electrodes in CRA were fabricated from HRB400 rebar with a diameter of 12.0 mm. As shown in Fig. 1, the electrodes were arranged as a 2 × 18 matrix with an interval of 5.0 mm, and then embedded in epoxy resin. Wires were attached to the rebar electrodes to provide the necessary connections to the measuring devices. The top section of each electrode in the rebar electrodes array (REA) was gradually ground down to 1000 grid with SiC paper, then degreased with acetone and rinsed with deionized water.

The nominal dimensions of the concrete prisms embedding REA were 150 × 150×450 mm^3. The water to cement ratio was 0.60. The 10 mm cover over the rebar of the concrete prisms was adopted to accelerate corrosion activity. After 24 h under laboratory conditions (Temperature: 20 ± 1 °C and Relative Humidity ≈ 75%), the test specimens were demolded. The specimens were moist-cured for 28 days at 25 ± 1 °C at a relative humidity of not less than 95% before subjection to the exposure conditions [9].

2.2. Exposure conditions

Following the curing period, the concrete prisms were placed longitudinally in the simulated marine environments. The three exposure conditions of the splash, tidal and submerged zones were created in the marine environment simulation equipment (MESE). As shown in Fig. 2, the MESE system consisted of two tanks, one pump and one blower. The upper tank was for the specimens, and the bottom one was used as a seawater reservoir when the water level was adjusted. Specimens were placed vertically in the upper tank, and were subjected to a five-day period for the accelerated corrosion tests. A two-days high tide cycle was followed by a three-days low tide cycle in the whole period. One-third of each prism was immersed in the low tide cycle, while two-thirds of that were submerged in the high tide cycle.

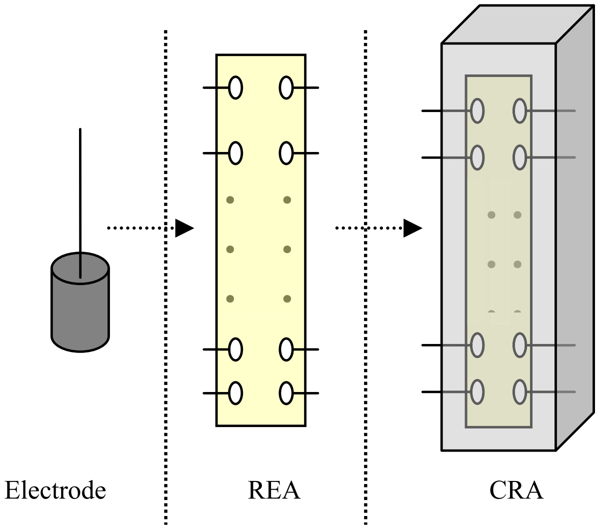

Fig. 1. Schematic diagram of the CRA preparation.

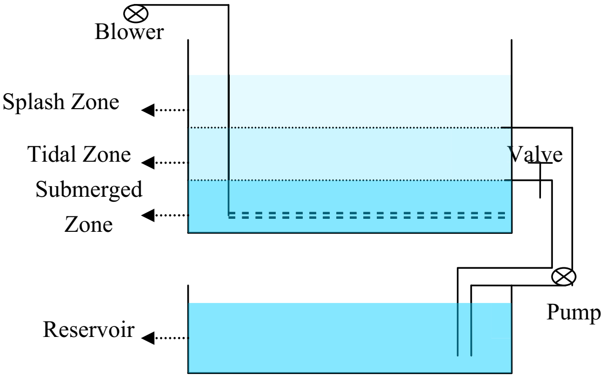

Fig. 2. Schematic of the marine environment simulation equipment.

2.3. Test methods

To simulate a long reinforcement bar, the rebar electrodes of column were shorted together by the copper wires so that electrons could move freely among them. This column was labeled as the "A", and the rebars were labeled from the bottom up as "A1, A2, . . ., A17, A18", respectively. The rebars of the other column were labeled as "B1, B2, . . ., B17, B18", and they were not shorted together. In this work, the corrosion of these rebar electrodes in the REA was characterized by the WBE, LPR and EIS techniques.

2.3.1. Galvanic current test

Once the concrete prisms were placed vertically in the simulated marine environments, the rebar electrodes in the A column were shorted together by wires. The galvanic currents of these rebar electrodes were measured on a regular basis using the WBE measurement system with modular hardware controlled by the LabVIEW software (NI)[10].

2.3.2. Linear polarization resistance

Corrosion rates of each rebar electrode in concrete prism subjected to the simulated marine environments were monitored on a regular basis using the DC linear polarization resistance method. The corresponding rebar embedded in concrete was used as the working electrode, which had a 1.13 cm^2 area of cross section, and was 10 mm inside from the concrete surface. A saturated calomel electrode (SCE) was used as the reference electrode, and the counter electrode was a platinum net of 2 × 2 cm^2. The linear polarization measurement was conducted in the range of