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Comparative studies of experimental and numerical techniques in measurement of corrosion rate and time-to-corrosion-initiation of rebar in concrete in marine environments

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ABSTRACT

The evaluation of the corrosion process for estimating the service life of concrete structure is of great importance to civil engineers. In this paper, the effects of different exposure conditions (i.e., tidal and splash zones) on macrocell and microcell corrosion of rebar in concrete were examined on concrete specimens with different w/c ratios in the Persian Gulf region. Experimental techniques such as macrocell corrosion rate measurement, Galvanostatic pulse, electrical resistivity, half-cell potential measurement, and numerical techniques were used to determine the corrosion rate and time-to-corrosion-initiation of rebar. Results showed that corrosion rates in the splash zone were higher than the ones in the tidal zone. This indicates that the propagation of corrosion in the splash zone is faster than the one in the tidal zone. There was also a strong correlation between the experimental results and those obtained from a numerical model in both tidal and splash zones.

1. Introduction

Corrosion of embedded steel rebars in concrete structures in chloride-contaminated environments is the most common cause of premature deterioration and failure of concrete leading to the reduction of its service life and thus, tremendous economic losses [1]. Corrosion of rebars in reinforced concrete in aggressive environment is often caused by the penetration of chloride into concrete pores after a prolonged exposure [12–4]. Several factors are influential on the corrosion process; some of them are related to the properties of the reinforced concrete materials, such as the quality of concrete and the type of rebar (e.g. black steel, stainless steel, and galvanized steel); others are related to environmental factors such as exposure condition, temperature, and humidity. For initiation of the corrosion process, the amount of chloride at the level of rebar in concrete must reach to a certain threshold called critical chloride content [5–9]. Once chloride reaches the critical amount, steel starts corroding due to the deterioration of the passive oxide layer on steel rebars [10–19].

There are two different types of chloride-induced corrosion in concrete: microcell corrosion and macrocell corrosion. Macrocell corrosion with a small anode and a large cathode frequently occurs in chloride-induced corrosion of rebars in concrete and is responsible for highly localized corrosion attacks and thus, localized cross-section reduction of rebar. In addition to the macrocell corrosion, there is another corrosion mechanism known as microcell corrosion in which the anode and cathode sites are located close to each other in micro-scale on the surface of steel. These two corrosion mechanisms usually occur on the surface of rebar in concrete at the same time; therefore, the corrosive action of both mechanisms would be superimposed [20].

In spite of numerous investigations carried out on different aspects of corrosion, few studies have been conducted towards the simultaneous occurrence of microcell and macrocell corrosion, especially when the structure is exposed to a splash zone [21–23]. Due to the higher presence of oxygen in a splash zone, this zone is more aggressive than a tidal zone. As a result, the evaluation of corrosion at a splash zone compared to a tidal zone is more important as the corrosion of rebar in this zone is more severe. Therefore, the corrosion of reinforced concrete elements exposed to the splash zone plays a key role in the overall service life of structures in marine environment.

In this study, reinforced concrete specimens with different water to cement ratios were prepared and exposed separately to tidal and splash zones for 650 days in the Qeshm Island in the Persian Gulf region. The environmental conditions of this zone, as presented in Table 1, clearly show that the relative humidity and average temperature of this region are quite high [24]. The combination of the environmental conditions and high chloride

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Table 1
Average temperature and relative humidity of Qeshm Island in the different months of year.

Zone	January	February	March	April	May	June	July	August	September	October	November	December	Ann.
Average temperature (°C)	18.1	19.7	22.4	26.2	29.9	32.7	34.6	34.3	32.3	29.1	24.3	20.5	27
Average relative humidity (%)	69	70	72	70	69	71	69	70	73	69	63	65	69

concentration of seawater have made this marine environment one of the most severe geographical regions for reinforced concrete structures in the world [25,26]. Unlike previous studies [27,28], in this study the specimens in the splash zone were completely separated from those in the tidal zone so that the splash zone effect can be systematically compared to that of the tidal zone. A number of field techniques such as the macrocell corrosion potential, Galvanostatic pulse, electrical resistivity, and half-cell potential measurement were used to determine the rate of corrosion and time-to-corrosion-initiation. Although these techniques have been used by many researchers to evaluate the corrosion performance of rebar in concrete, few research studies have been conducted to compare the efficiency and accuracy of these techniques in field application. Therefore, a multi-technique approach was implemented in this study to provide some insight into the relative performance of these methods for the assessment of corrosion in concrete structures. In addition, a comparison was made between the experimental results of this work with those obtained from a recently developed model for numerical prediction of corrosion rates in reinforced concrete structures [29,30].

2. Experimental program

2.1. Materials

Type II Portland cement was used in this experiment. The crushed limestone local source aggregate and river sand were used as coarse and fine aggregates, respectively. The total bulk density of the aggregate was about 1850 kg/m^3 with a maximum aggregate size of 19 mm. The chemical composition of the cement, gravel and sand used in this study is presented in Table 2. The polycarboxylate-based superplasticizer was used to achieve desired workability in different mixture proportion designs.

2.2. Mixture proportions

Four mixture proportions with different w/c ratios (i.e., 0.35, 0.40, 0.45, and 0.50) were used in concrete specimens. The amount of cement content was 400 kg/m^3 in all mixtures. The details of mixture proportions are provided in Table 3.

2.3. Specimen details

Concrete specimens of 550 × 300 × 200 mm were prepared with three 14 mm diameter rebars at the top and six rebars with the same diameter at the bottom with 30 mm concrete cover thickness from both sides. They were placed in such a way that for every anode rebar at the top, there were two cathodes rebars at the bottom to create a single corrosion cell (Fig. 1a). Thus, three corrosion readings could be recorded from three different corrosion cells which made the outcome of the results more reliable. The specimens were demoulded after 24 h and were immersed into water for two days at room temperature (23 ± 1 °C). The surrounding sides of the specimens, including the bottom of the specimens, were coated by an epoxy resin so that only the top face of the specimens remained uncoated to be exposed to the marine environment. The epoxy resin was dried after the specimens were exposed to air for one day. All specimens were then transferred to the exposure site and placed in the tidal and splash zones for 650 days. As shown in Fig. 1b, the top surface of the specimens was in the upward direction. In the tidal zone the height of the specimens' location was selected such that the time period during which the specimens were in drying condition was the same as that in the wetting condition. In other words, the specimens were fully saturated during the half of exposure time. In splash zone, the specimens were placed at a higher elevation than that of the tidal zone so that they never experienced immersion during the exposure time and only seawater sprayed the surface of concrete. The first reading was conducted after three months of exposure while the subsequent measurements were carried out every month.

2.4. Methods of measurement

The macrocell and microcell corrosion were investigated in this study because these are the most common corrosion mechanisms that occur in reinforced concrete structures in marine environments. For this reason, various methods of corrosion measurements commonly used for the condition assessment of the reinforced concrete structures, such as the macrocell current, half-cell corrosion potential, Galvanostatic pulse, and electrical resistivity measurement techniques were employed in this work. It should be noted that all measurement techniques were applied on all three corrosion cell units of each specimen. Therefore, three measurements for each concrete specimen were recorded and the corresponding average was reported in this study.

2.4.1. Macrocell measurement

According to ASTM G109-99a [31], the initial macrocell corrosion of each corrosion cell unit was determined by measuring the voltage across a 100 Ω resistor connected between the top and bottom rebars using a high impedance voltmeter. The voltmeter was connected to the two sides of the resistor for the measurements of the electrical potential. The corrosion rate was then calculated by dividing the measured potential (V) by 100 Ω. In accordance with ASTM G109-99a, the corrosion initiates when the corrosion current reaches to 10 μA.

2.4.2. Microcell measurement

The microcell corrosion was measured using the Galvanostatic pulse technique. In this method, a current pulse (I_{app}) in the range

Table 2
Chemical composition of the materials.

Components (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	L.O.I
Cement	21	5	3.5	63	1.8	1.6	0.5	0.6	2
Gravel	7.88	0.53	1.07	44.12	4.61	0.1	0.03	0.36	40.86
Sand	50.73	5.91	7.45	15.16	7.33	0.003	1.46	0.65	10.21