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Influence of compression fatigue on chloride threshold value for the corrosion of steels in simulated concrete pore

Linhua Jiang [a,b,*], Hao Liu [a], Hongqiang Chu [a], Chenglong Zhu [a], Chuansheng Xiong [a], Lushen You [a], Jinxia Xu [a], Yan Zhang [a], Yujiao Qin [a]

[a] College of Mechanics and Materials, Hohai University, 1 Xikang Rd., Nanjing 210098, PR China
[b] Engineering Research Center on New Materials and Protection in Hydraulic, Jiangsu Province, 1 Xikang Rd., Nanjing 210098, PR China

HIGHLIGHTS

- The influence of compression fatigue on chloride threshold value was examined.
- The chloride threshold values vary with different fatigue life cycles.
- The corrosion behavior depends on the grain size of the steels.

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ABSTRACT

Compression fatigue test was performed on stress level 0.8 for a group of fixed cycle numbers. The steels were soaked in the saturated $Ca(OH)_2$ solution, which was used as simulated concrete pore solution. NaCl was chosen as the sources of chloride ion to corrode the steels. The chloride threshold value (CTV) was detected by combining the open-circuit potential (E_{corr}) with corrosion current density (I_{corr}), which was obtained by electrochemical impedance spectroscopy (EIS). The changes of microstructure that caused by the compression fatigue were observed by optical microscopy (OM) and scanning electron microscopy (SEM). The results showed that the CTV first increased and then decreased with increasing the fatigue cycle times under a certain stress level and range of fatigue life cycles. The grains of the steels became finer and cracks appeared on the protective firms which formed quickly on the surface of the steels. The capacitive arcs under no compression fatigue decreased gradually, while the ones under compression fatigue presented no regularity due to the uneven distribution of the protective films. Cracks on the protective films propagated because of sustaining compression fatigue, which degenerated the later resistances of the steels to chloride ions. Meanwhile, the ranges of corrosion currents were declined.

1. Introduction

The early deterioration of reinforced concrete structures is one of the major concerns to construction industry all around the world, while the chloride-induced corrosion of steel bars dominates the durability of concrete structures exposed to marine environments.

The breakdown of the passive film occurs when the chloride concentration exceeds to a critical value. The chloride threshold value (CTV) is considered as an essential parameter for assessing the probability of reinforcement corrosion and predicting service life. Based on this, numerous investigations have been performed on the CTV. Researchers [1–3] found that chloride salt types affected the threshold level of reinforcement corrosion in simulated concrete pore solutions. Yuan [4] and Angst [5] pointed that most studies focused on the influence of parameters, such as steel-concrete interface, moisture and temperature, concrete mix proportions and so on.

Many constructions, such as bay bridges, tidal gates and harbors, served in marine environments or compression fatigue situations, thus it is necessary to investigate the influence of compression fatigue on the threshold level of the corrosion of steels. However, there are few reports about influences of compression fatigue on chloride threshold value for the corrosion of steels. In this work, the influence of compression fatigue on chloride threshold value for the corrosion of steels had been investigated in $Ca(OH)_2$ solution. The initiation of pitting corrosion for

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* Corresponding author at: College of Mechanics and Materials, Hohai University, 1 Xikang Rd., Nanjing 210098, PR China. Tel./fax: +86 25 8378 6046.
E-mail address: hhulhjiang@gmail.com (L. Jiang).

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the steel reinforcement was detected by combining the open-circuit potential (E_{corr}) with corrosion current density (I_{corr}), which was measured by electrochemical impedance spectroscopy (EIS). Besides, the effect of microstructure on corrosion of the steels was carried out using optical microscopy (OM) and scanning electron microscopy (SEM).

2. Experimental

2.1. Fatigue test

The specimen for the fatigue tests was the low-carbon steel, which was 70 mm in gauge length and 10 mm in diameter. The low-carbon steel was located in a self-designed localizer, which consists of support, dimensional constraint, and the wind-up key. The chemical compositions (wt%) of the low-carbon steel is shown in Table 1. Fig. 1 exhibits the profile of the localizer.

Prior to application, the steel rods were firstly ground with silicon carbide abrasive paper to remove the as-received mill scale on their surfaces, washed in distilled water and then degreased in acetone. All chemical reagents applied in this study were analytical reagent (AR) grade.

The cylindrical fatigue specimens were tested in an electro-hydraulic-servo testing machine under load control using sinusoidal loading at a frequency of 7 Hz. A stress ratio, i.e. $|\sigma|_{max}/|\sigma|_{min} = 0.1$, was used. All experiments were performed at ambient temperature varying between 20 °C and 25 °C.

The group of coupons tested, 4 in total, was partitioned as follows: group A for static test to provide baseline data, while groups B, C and D were tested under axial cyclic stress at various fatigue life cycles: 50,000,100,000 and 150,000 respectively. Each test was repeated for 7 times to ensure a good repeatability of experiment results.

2.2. Electrochemical test

The lateral surface of the steel rods had an exposed area of 10.996 cm^2, and the remaining areas had been sealed by means of epoxy resin and hot-shrinkable tube. An electrical contact was achieved through a thick copper wire soldered to the other end surface of the specimen. The prepared steel electrode was presented in Fig. 2.

Saturated calcium hydroxide ($Ca(OH)_2$) solution (pH > 12.5), which had been prepared by adding excessive $Ca(OH)_2$ solid into the distilled water, was to simulate the alkaline pore solution of concrete. Some residue of insoluble $Ca(OH)_2$ was remained in the solution. During this experiment, the contact with the air was minimized to avoid carbonation.

The electrochemical measurements were carried out via a Parstat 2273 Advanced electrochemical system on a three-electrode cell, with the steel electrode as working electrode, a platinum electrode as counter electrode, and a saturated calomel electrode (SCE) as a reference electrode. Subsequent to the E_{corr} measurements, EIS scan was carried out by applying a sinusoidal potential perturbation of 10 mV at the open circuit potentials with frequency sweep from 100 kHz to 10 mHz. After this, the obtained EIS spectras were analyzed with an equivalent-circuit to obtain the values of polarization resistance (R_p) by ZsimpWin software.

Prior to electrochemical measurement, for simulating field conditions and promoting a reproducible surface condition, the steel rods were immersed in the saturated $Ca(OH)_2$ for 7 days to produce the passivation film on their surfaces. The chloride ions in the solution were supplied by sodium chloride and added gradually in several steps. The intervals of the addition were 2*d* and each dosage was 0.01 mol/L. Before every addition, the pH values of the solution, the corrosion potential E_{corr} and the EIS spectra are obtained.

3. Results

3.1. E_{corr}

The demarcation value of E_{corr} between the passive and active specimens is −350 mV [6]. Fig. 3 shows the variations of the E_{corr} for the specimens in the saturated $Ca(OH)_2$ solutions with the addition of chloride ions derived from NaCl solution . With the concentration of the chloride ion increased, the potential of steel (E_{corr}) decreased gradually. Furthermore, when the concentration of chloride ion increased to a certain value, the potential of steel (E_{corr}) for each specimen exhibited a sudden shift to negative value. The critical concentration of sample A, B, C and D were 0.03 mol/L, 0.06 mol/L, 0.04 mol/L, and 0.04 mol/L respectively. It can be obviously seen that the CTV increased with the cycles of compression fatigue and the growth rate of B was higher than C and D.

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

C	Si	Mn	S	P	Fe
0.22	0.30	0.65	0.05	0.045	Balanced

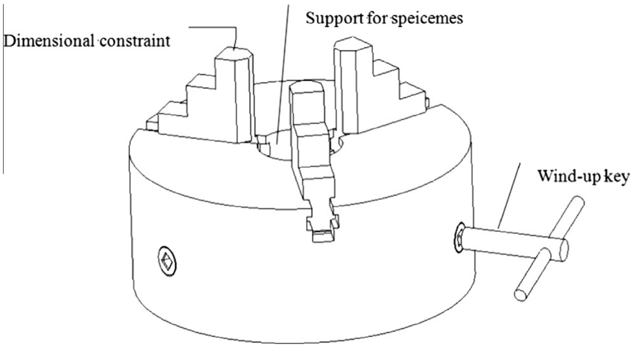

Fig. 1. Schematic map of the self-designed localizer for fatigue testing.

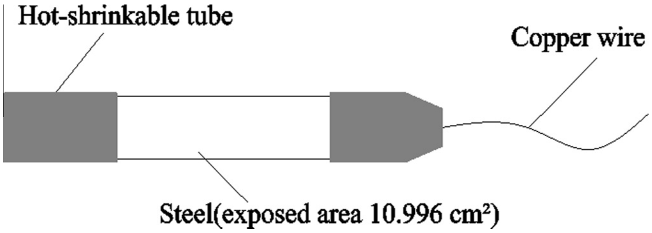

Fig. 2. Steel electrode (unit: mm).

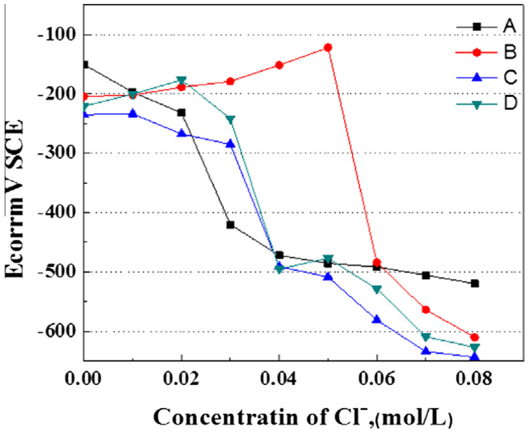

Fig. 3. Electrochemical potential of steels in function of the addition of chloride ions.

Besides, once the addition of chloride ions of sample A reached 0.03 mol/L, the curve changed gently and the value of E_{corr} stabilized at about −520 mV. While for sample C and D, the curves changed greatly and the value of E_{corr} stabilized at about −600 mV after the addition of chloride ions reached their CTV.

3.2. EIS

Figs. 4 and 5 depict the Nyquist plots of different steels in function of the addition of chloride ions. The capacitive arc decreased sharply when the chloride ions were added to a certain concentration, which indicated the breakdown of the passive film. From