Research Article

The Coupled Effect of Temperature and Carbonation on the Corrosion of Rebars in the Simulated Concrete Pore Solutions

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The reinforced concrete structures have to survive high temperature and carbonation at low latitude region. The research on the effect of temperature and the effect of carbonation are vital to the corrosion of the rebars in concrete structures. The coupled effect of temperature and carbonation on the corrosion of rebars was researched by using the open circuit potential (OCP), the electrochemical impedance spectroscopy (EIS), and the potentiodynamic polarization (PP) measurement in the simulated concrete pore solutions (SPSs). The high temperature environment is conducive to the formation of passivated surface of rebars in SPSs, but the dissolution velocity of passivated surface is higher. The rebars have the greater capacity of passivity at lower temperature. The corrosion rate of rebars at higher temperature is smaller in moderate pH value (10.6) SPSs. The rebars suffer from serious corrosion in the pH = 9.6 SPSs at 318 K temperature.

1. Introduction

Corrosion of rebars in concrete is crucial to the durability of reinforced concrete structure, especially in an aggressive environment. Investigations of the corrosion of rebars in concrete structures are being intensively pursued, because such corrosion can cause serious damage to concrete, and eventually failure of the structure [1]. Carbonation induced corrosion is a major cause of decay of reinforced concrete structures in the fields of buildings, civil engineering bridges, or historical monuments [2, 3]. The process of carbonation causes a pH decrease (from around 13 to around 8) in the solution that presents in the concrete pores [4]. As long as the rebars are in a high alkalinity environment concrete, they remain passive. The consumption of portlandite that the natural ageing carbonation process leads to induces the decrease of the pH of the concrete cover. If the pH of SPSs reaches a low value, the active corrosion of rebars can take place [2].

Temperature is a key factor in chemical reactions kinetics, including corrosion, obviously. The concrete cover of the rebars is a dynamic system that pore structure and chemical composition change with exposure time to the environment [5]. The presence of Cl^-, CO_2, or SO_4^{2-} is frequently cited as the main factors responsible for the onset and propagation of decay [6], that is, cracking due to corrosion of the rebars. Many papers can be found in the literature that describes the phenomenology of the process [7] and the effects of individual factor. However, studies devoted to the coupled effect of temperature and carbonation are rather scarce [8].

The reinforced concrete structures have to survive high temperature and carbonation at low latitude region. A large number of laboratory studies had been conducted, most of which focused on a single factor that impacts the corrosion process such as penetration of Cl^-, carbonation of concrete, or loading levels [9–13]. Since reinforced structures generally experience complex environmental and mechanical loadings, there were also a rapidly increasing amount of research into corrosion of rebars in concrete by coupled factors [14–16], but many combined aspects have not yet been examined in sufficient detail. Therefore, the present study is focused on the coupled effect of temperature and carbonation on the corrosion of rebars in SPSs.

TABLE 1: Chemical composition and nominal pH of fresh simulated pore solutions.

Composition	pH	NaOH (mol/L)	KOH (mol/L)	Ca(OH)$_2$ (mol/L)	NaHCO$_3$ (mol/L)
SPSs1	9.6	0.6	0.2	0.001	4.39
SPSs2	10.6	0.6	0.2	0.001	1.16
SPSs3	11.6	0.6	0.2	0.001	0.84
SPSs4	12.6	0.6	0.2	0.001	0.76

FIGURE 1: The effect of temperature and pH on the OCP of rebars in SPSs.

FIGURE 2: Equivalent circuit used in numerical fitting of the impedance data.

2. Experimental

2.1. Specimen Preparation. The thread steel bar (HRB400) specimens were prepared for this study. The specimens were cut to 30 mm lengths from black steel rebar of 12 mm nominal diameter. The average area of the exposed rebar surfaces (cross section) was 1.1 ± 0.03 cm^2. The unexposed faces were sealed with epoxy resin. Before exposure, the as-received surfaces were mechanically polished using 400, 800, and 1200 emery papers and lubricated using distilled water. The polished samples were cleaned with acetone, washed using distilled water, dried in air, and stored over a desiccant.

2.2. Experimental Setup. A 1 L glass container was used as a test cell in this study. Four different types of water solutions were selected as the simulated concrete pore solutions (SPSs). The chemical compositions of the SPSs are presented in Table 1 [17]. The lower pH solution was intended to present pore water within a carbonated concrete environment. Approximately 0.8 L of SPSs was used in each glass container and its pH was monitored throughout the experiment. Because the results of deviation were less than 0.1, the effects on experimental results induced by pH fluctuation were ignored. A magnetic stirring bar was placed at the bottom of each container and was set to rotate at the lowest rate to continuously mix the solution homogeneously throughout the experiment, including the duration when the electrochemical measurements were conducted. Ambient temperature was held at 298 ± 2 K, 308 ± 2 K, and 318 ± 2 K.
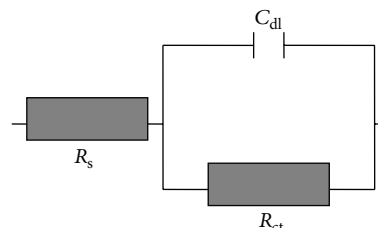
2.3. Electrochemical Measurements. For assessing the corrosion conditions of steel bars, the electrochemical measurements were carried out. The rebar was used as working electrode, a platinum net as counter electrode, and a saturated calomel electrode (SCE) as reference electrode. During the course of the experiment, the rebar electrode always was immersed in the SPSs. For the open circuit potential (OCP) measurement, the electrochemical impedance spectroscopy (EIS) measurement, and the potentiodynamic polarization (PP) measurement, Autolab Aut84458 Advanced Potentiostat/Galvanostat/FRA system was applied. The EIS was measured with a sinusoidal potential excitation of 15 mV amplitude in the frequency range from 100 KHz to 10 mHz at corrosion potential. The PP was measured by potential scanning from -800 to $+500$ mV versus corrosion potential at a sweep rate of 1 mV/s.

3. Result and Discussion

3.1. The Effect of Temperature and pH on the OCP. As can be seen from Figure 1, with the pH of SPSs rising, the OCP of rebar increases at lower temperature (298 K) except for the pH = 10.6. The OCP of rebar that is immersed in the pH = 10.6 SPSs is lowest (-229 mV). The OCP of rebar decreases with pH of SPSs rising at higher temperature (308 K and 318 K), but the OCP of rebar reduces sharply in pH = 9.6 and 318 K SPSs. The OCP is the reflection of the corrosion tendency of rebar in SPSs. The rebar is prone to corrosion in higher temperature and lower pH SPSs. The corrosion of rebar is serious in the pH = 9.6 and 318 K SPSs. The rebar has the best corrosion-resistance in the pH = 10.6 and 318 K SPSs.

3.2. The Effect of Temperature and pH on the Passivation Film of Rebar. The passivation film of the rebars was evaluated by EIS. The shape of the EIS spectra can be described by using the RC network depicted in Figure 2. The series resistance (R_s) accounts for the ionic conduction in the SPSs, whereas the other elements refer to the double layer capacitance at the
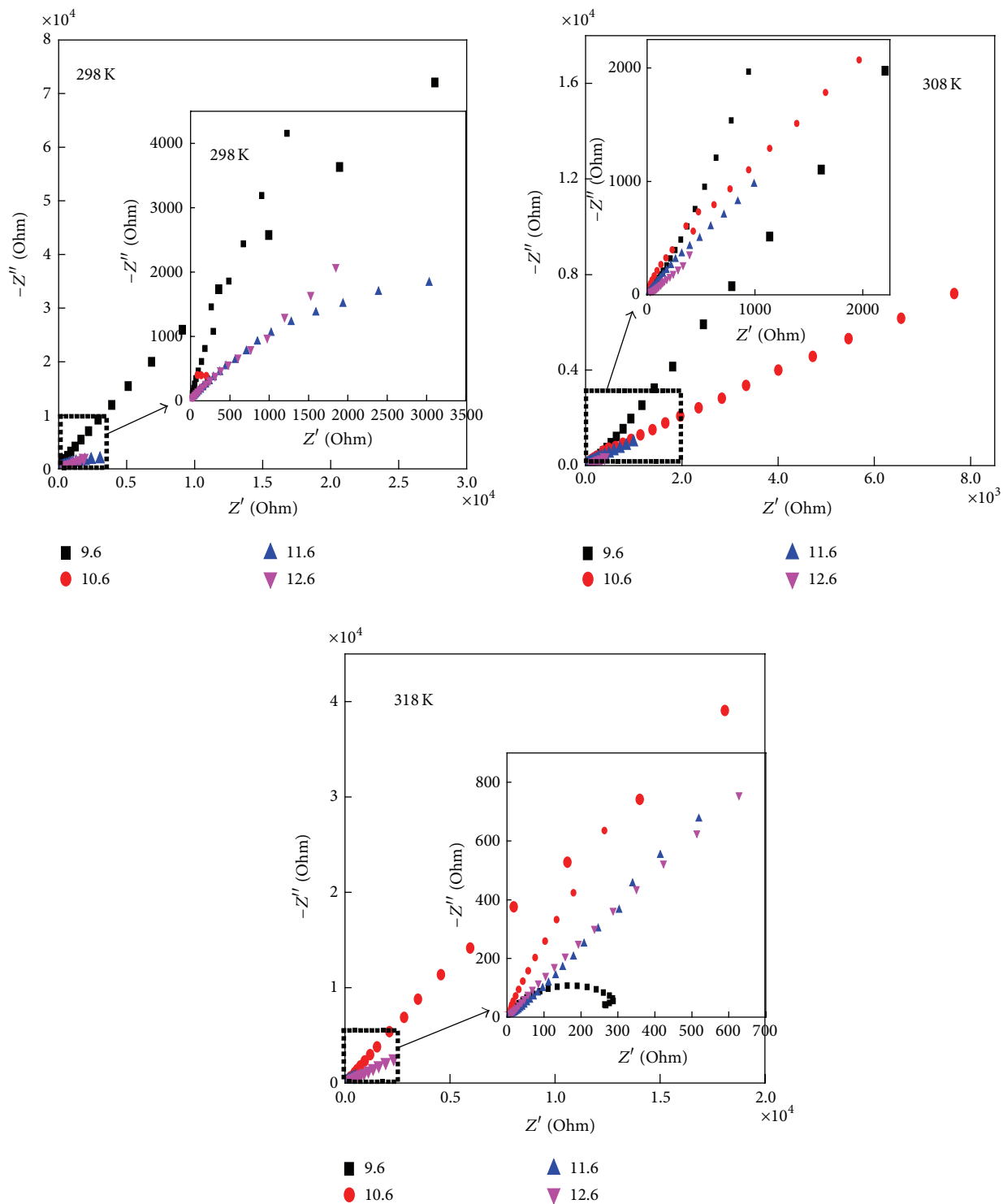
FIGURE 3: The impedance spectra of rebars after 3 days of exposure to the SPSs.

rebar/SPSs interface (C_{dL}) and the charge transfer resistance (R_{ct}).

Figure 3 depicts the impedance spectra of rebars after 3 days of exposure to the SPSs at 298 K, 308 K, and 318 K. At different temperature (298 K, 308 K, and 318 K) and in different pH value (9.6, 10.6, 11.6 and 12.6) SPSs, the EIS of

rebars was measured. The R_{ct} and C_{dL}, which were obtained from numerical fitting, of the rebars are presented in the Table 2. The charge transfer resistance is inversely proportional to the corrosion rate [18]. The corrosion rate of rebars at higher temperature is bigger than that at lower temperature. The corrosion rate of rebars at higher temperature is smaller
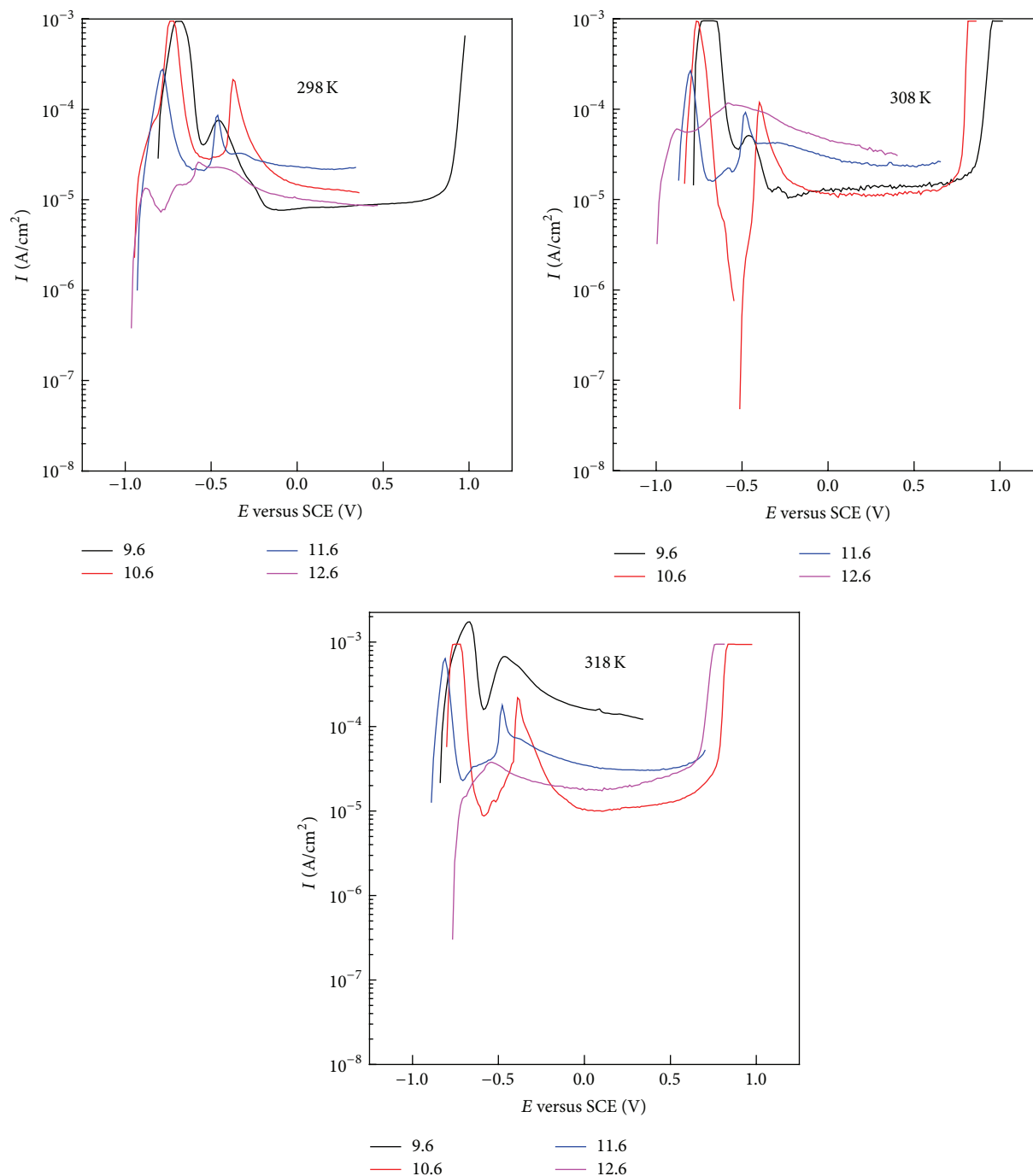
FIGURE 4: The potentiodynamic polarization curves of rebars in different pH value SPSs.

in moderate pH value (10.6) SPSs. The capacitive response reveals a situation of passivity for the samples [18]. The rebars have the greater capacity of passivity at lower temperature. It is favourable to passivation that the rebars were soaked in moderate pH value (11.6) SPSs. The effect of temperature and pH on the corrosion rate and greater capacity is noteworthy.

3.3. The Effect of Temperature and pH on the Corrosion Current of Rebar. The corrosion current of the rebars, which were

soaked in the different pH and different temperature SPSs, was measured by using potentiodynamic polarization measurements. Figures 4 and 5 represent the potentiodynamic polarization curves of rebars. From **Figure** 4, the polarization plots of rebars soaked in the lower pH value (9.6, 10.6, and 11.6) SPSs exhibited an activation current peak that lie between −0.5 V and −0.25 V. The rebars, which were soaked in higher pH value (12.6) SPSs, were in the passivation state between −0.5 V and 0.75 V. The passive current of rebars
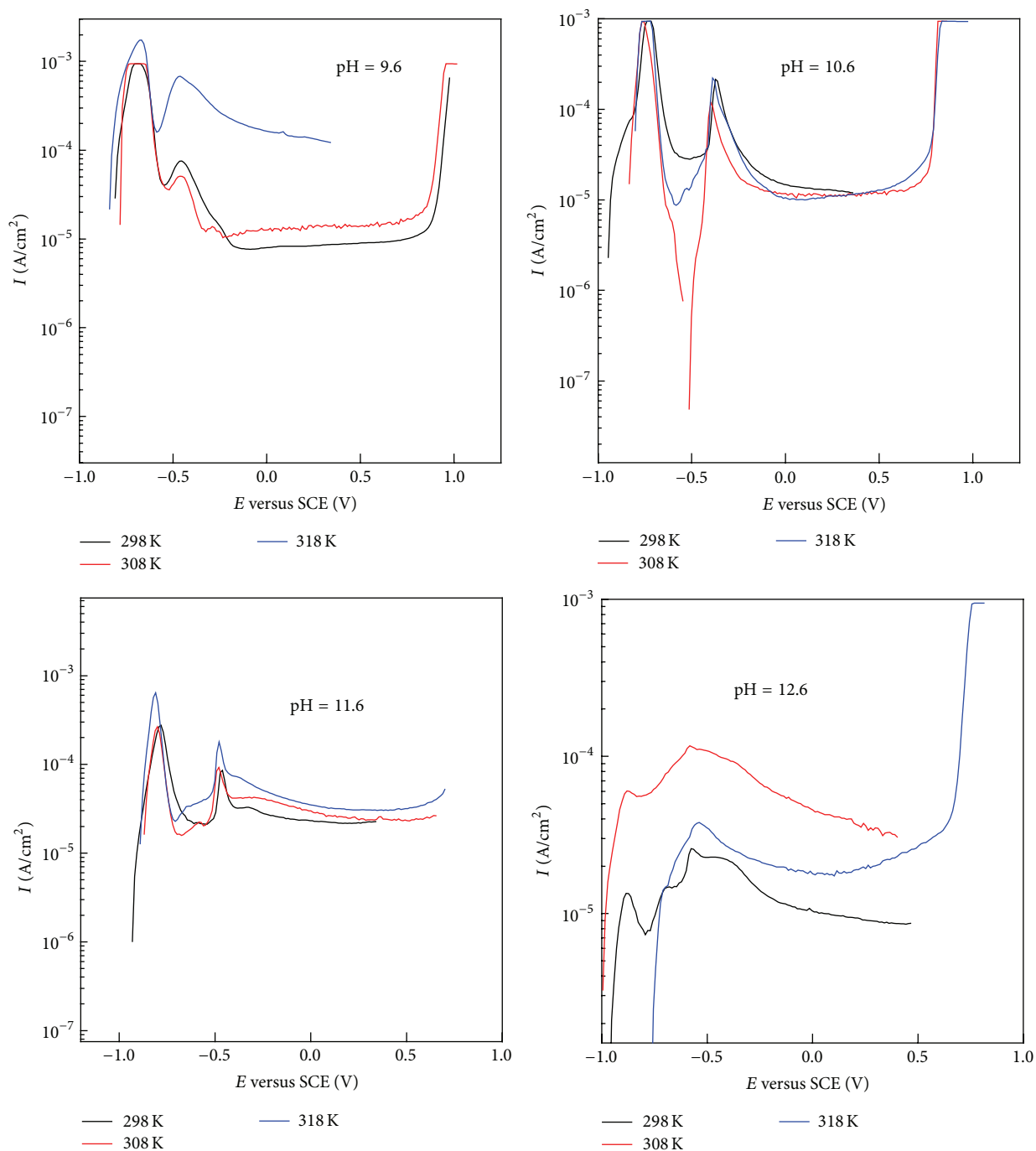
FIGURE 5: The potentiodynamic polarization curves of rebars at different temperature.

in the higher pH value SPSs is bigger than that of rebars in lower pH value SPSs. This means that the dissolution velocity of passivated surface is bigger if the pH of the SPSs is very high. From Figure 5, the high temperature environment is conducive to the formation of passivated surface. At 318 K temperature, the rebars suffer from serious corrosion in the pH = 9.6 SPSs and the rebars have the strong corrosion resistance in the pH = 10.6 SPSs. This means that the high

temperature and high pH environment are conducive to the formation of passivated surface. The potentiodynamic polarization results also support the findings of EIS studies.

4. Conclusions

The reinforced concrete structures have to survive high temperature and carbonation at low latitude region. The research

TABLE 2: The R_{ct} and C_{dl} obtained from numerical fitting of the rebars.

pH	R_{ct} (Ohm)			C_{dl} (μMho)		
	298 K	308 K	318 K	298 K	308 K	318 K
9.6	8790	865	251	87	262	1320
10.6	619	1850	3290	762	122	139
11.6	543	488	48	644	2290	1330
12.6	1190	106	173	1940	1880	637

on the coupled effect of temperature and carbonation is vital to the corrosion of the rebars in concrete structures. The results presented above allow to us conclude the following.

(1) The high temperature environment is conducive to the formation of passivated surface of rebars in the simulated concrete pore solutions. But the dissolution velocity of passivated surface is bigger in the high temperature SPSs. The rebars have the greater capacity of passivity at lower temperature.

(2) The rebars soaked in the lower pH value (9.6, 10.6, and 11.6) SPSs exhibit an activation process. In the higher pH value (12.6) SPSs, the rebars were always in the passivation state; however, the passive current is not smallest. The corrosion rate of rebars is smallest in moderate pH value (10.6) SPSs at higher temperature. The rebars suffer from serious corrosion in the pH = 9.6 SPSs at 318 K temperature.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

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