Galvanic Corrosion Between AISI304 Stainless Steel and Carbon Steel in Chloride Contaminated Mortars

Xingguo Feng[1,2,], Jianqu Liu[2], Cen Hang[2], Zuocheng Lu[2], Yukun Jiang[2], Yiwen Xu[3], Da Chen[1,2,]*

[1] Jiangsu Key Laboratory of Coast Ocean Resources Development and Environment Security, Hohai University, Nanjing 210098, Jiangsu, China
[2] College of Harbour, Coastal and Offshore Engineering, Hohai University, Nanjing 210098, Jiangsu, China
[3] Dayu College, Hohai University, Nanjing 210098, Jiangsu, China
*E-mail: chenda@hhu.edu.cn

Galvanic corrosion between AISI304 stainless steel and carbon steel in mortars has been studied by open circuit potential, electrochemical impedance spectroscopy, and galvanic coupling currents. The corrosion state of the coupling rebar was also examined after removing the mortars. The results suggest that the carbon steel presents a high risk of galvanic corrosion in the initial stage when it is electrically coupled with stainless steel in the chloride-contaminated mortars. However, for the stainless steel promotes the passivation of carbon steel, the risk of galvanic corrosion on carbon steel significantly decreased as the time extends. In addition, the water-cement ratio of mortars does not have a dramatic influence on the galvanic corrosion between stainless steel and carbon steel in the chloride-contaminated environment.

1. INTRODUCTION

Corrosion of rebar is one of the main causes of reduction of the durability of concrete structures [1-3]. Since Borge [4] reported that a concrete wharf constructed by the stainless steel bar still performs well after service more than 60 years, the stainless steel rebar is thought to be the most effective method for increasing the durability of concrete structures in marine environments. For the high price of stainless steel, it is more reasonable and economical to use stainless steel bar in the important parts of structure. However, there is a significant difference in activity between the stainless steel and carbon steel. Thus, it is important to understand the galvanic corrosion behavior of the two

kinds of steel in concrete structure. Bertolini [5] and Abreu [6] studied the galvanic currents between carbon steel and stainless steel in the simulated pore solution and found that there is no practical risk of galvanic corrosion exists when carbon steel and stainless steel are electrically coupled. However, Qian and Du [7] found that the galvanic corrosion on carbon steel is obviously increased when the stainless steel is contamination by the rust of carbon steel. Dong [8, 9] studied the galvanic corrosion between carbon steel and stainless steel in chloride solution and sulfide solution, respectively. The authors noticed that the galvanic corrosion effect on carbon steel anode increases with the cathode/anode area ratios in the two solutions. In addition, Pérez-Quiroz [10] investigated the corrosion behavior of the welded joint between carbon steel and stainless steel in the calcium hydroxide solution. The results suggest that the connection between the two steels have sufficient corrosion resistance in the alkaline medium. To further understand the galvanic corrosion between stainless steel and carbon steel, the galvanic coupling between AISI304 stainless steel and carbon steel in chloride contaminated mortars are studied by open circuit potential (OCP), electrochemical impedance spectroscopy (EIS), and galvanic coupling currents in the present study. The corrosion state of the rebar was also examined after removing the mortar cover layers at 238 days. The results may offer some references for the design of stainless steel concrete structure in marine environments.

2. MATERIALS AND EXPERIMENTS

2.1 Materials

AISI304 stainless steel rod with 10 mm diameter was cut to a length of 50 mm. The carbon steel rebar (diameter: 10 mm) with a length of 50 mm was used. Before experiments, the stainless steel and carbon steel samples were ground with emery paper up to No.600. Copper wires were welded at one end of the steel samples. After that, Samples were degreased with acetone and both ends of the samples were coated with silica gel. After the silica gel coating solidified, a stainless steel sample was parallel tied to a carbon steel sample used a galvanized iron wire with 0.9 mm diameter. Then, the coupled stainless-carbon steel samples were embedded in the middle of the cylindrical mold with a size of $\Phi 40 \times 60$ mm and mortar was poured into the mold. The mortar only immersed with a single stainless steel or carbon steel bar was used as the controlled sample. Curing for 24 hours, the mortar samples were removed from the molds and immersed in the 5.0% sodium chloride solution. Mortar was mixed with ordinary Portland cement (P.O 42.5) and river sand at a ratio of 1:3. To study the effects of water-cement ratios (w/c) on the galvanic corrosion between the stainless steel and carbon steel, the ratios including 0.5, 0.6, 0.7, and 0.8 were designed for mortar and the prepared samples are shown in Figure 1. Some sodium chloride (3.0% weight of cement) was added to the mortar to accelerate the corrosion of rebar.
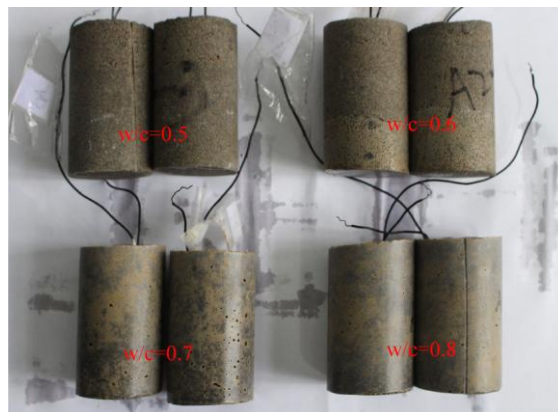
Figure 1. Photograph of the coupling stainless-carbon steel mortars with various water-cement ratios.

2.2 Experiments

All electrochemical tests were conducted by using a CS350 workstation (Corrtest Instrument, China). A classical three-electrode cell was applied: a saturated calomel electrode (SCE), a platinum plate and the steel sample in mortars are used as the reference, counter and working electrodes, respectively. The OCP and EIS of the single stainless steel, the single carbon steel, and the coupled carbon steel samples in mortar were separately tested. The EIS measurements were performed at frequencies ranging from $10^5 \sim 10^{-2}$ Hz. During the measurements, an AC perturbation of 10 mV was applied, at the OCP, to the steel electrode. The coupling potential and galvanic corrosion currents between the tied stainless steel and carbon steel in the chloride-contaminated mortars were recorded. The corrosion states of the coupled stainless steel and carbon steel in different water-cement ratio mortars also were examined after 238 days.

3. RESULTS AND DISCUSSION

3.1 Corrosion of the single steel in chloride contaminated mortar

As Figure 2 shows, for the single stainless steel or carbon steel bar in the chloride-contaminated mortar, the OCP of samples obviously decreased with the increasing water-cement ratio. Both the stainless steel and carbon steel in the mortars prepared with water-cement ratio at 0.5 presented the highest OCP. In addition, the OCP of the stainless steel samples is about 150 mV higher than those of the carbon steel in mortars with the same water-cement ratio. This situation is consistent with some earlier reports [5]. Bertolini also found that there is a similar difference in corrosion potential between 316L stainless steel and carbon steel in concrete with 3% NaCl. This situation should be attributed to the highly passivity of the stainless steel in the concrete.
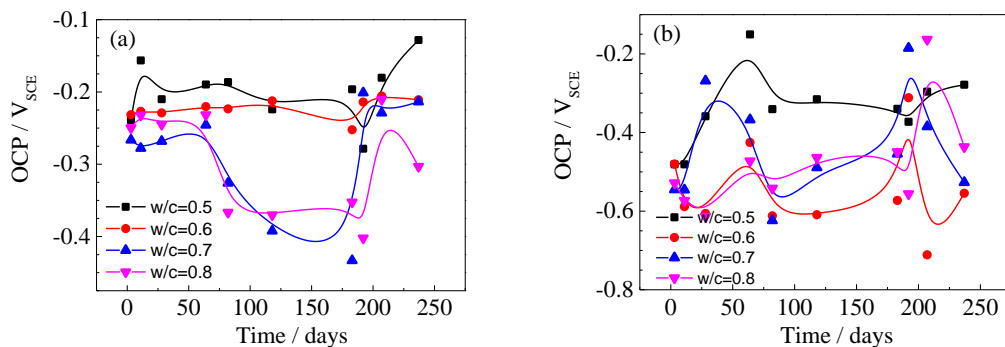
Figure 2. OCP of single rebar in mortars with various water-cement ratios in 5% NaCl solution, (a) stainless steel, (b) carbon steel.

The EIS of the single stainless steel and carbon steel bar were tested at 28 days and 238 days, respectively. As figure 3 shows, at the initial stage (28 days), the impedance values of stainless steel samples are significantly higher than these of the carbon steel ones. As the immersion time prolongs to 238 days, two capacitive loops were observed in the impedance spectroscopies. According to Ribeiro [11], the capacitive loop at high frequency is related with the concrete resistance and the films on the rebar, while the other capacitive loop at low frequency corresponding to the polarization resistance of the rebar. It can be concluded that the polarization resistance of steel in mortars increased with time as the radius of low frequency capacitive loop increased (figure 3). This situation indicates that the steel in the chloride contaminated mortars also can passivation. On the other hand, there is no obviously different in the impedances of the two steel after 238 days. Meanwhile, the water-cement ration of mortars does not show significantly influence on the impedance of the steels. The impedance and OCP results of the single steel suggested that there is a high risk of galvanic corrosion for the coupling stainless steel and carbon steel mortars in the initial stage. However, the risk significantly decreased as the time extends. Similarly, Abreu [6] also reported that there is no coupling galvanic corrosion problem for the carbon steel bar when it is connect with stainless steel bar. The galvanic corrosion between stainless steel and carbon steel even is lower than that between the passive and activity carbon steel.
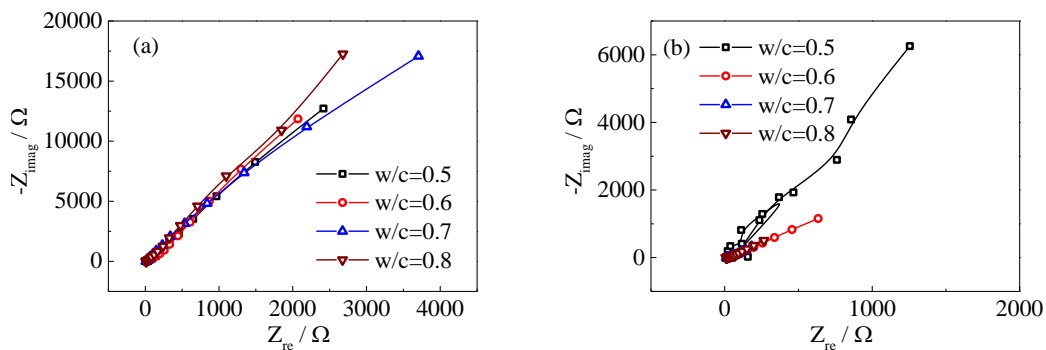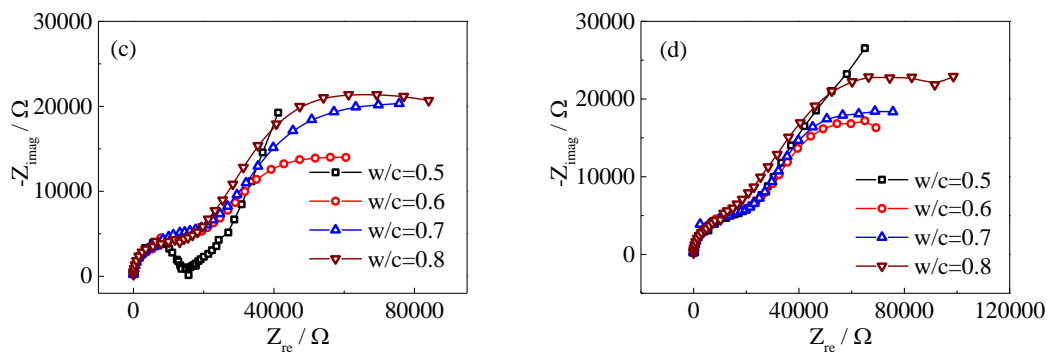
Figure 3. Nyquist plots of rebars in mortars after being immersed in a 5% NaCl solution for different time. (a) AISI304 stainless steel rebar for 28 days, (b) carbon steel rebar for 28 days, (c) AISI304 stainless steel rebar for 238 days, (d) carbon steel rebar for 238 days.

3.2 Galvanic corrosion of coupling stainless steel and carbon steel in chloride contaminated mortars

The coupling potentials of the connected stainless steel and carbon steel were tested at various time and the results are presented in figure 4. As the results show, the galvanic potentials decreased with the water-cement ratios at the initial 100 days. Then, most of the coupling potential maintains a stable value and the water-cement ratio does not show visibly affect the galvanic potentials. This result is consistent with the impedance results shown in figure 3, confirming that the coupling galvanic corrosion risk gradually decreased for the steel samples passivation in progress.
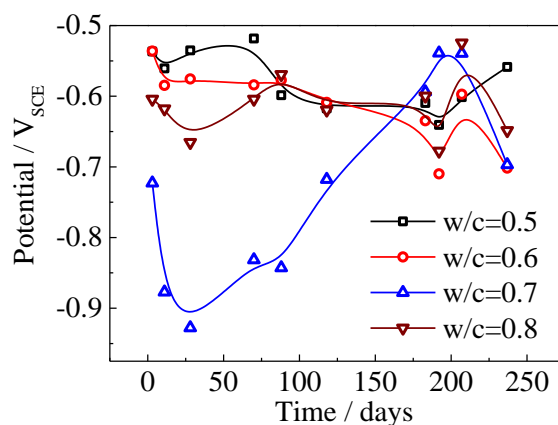

Figure 4. Evolution of galvanic potentials stainless steel and carbon steel in the chloride contaminated mortars.

The galvanic corrosion currents of the coupling stainless steel and carbon steel in various water-cement ratio mortars were measured at 28 days and 238 days, respectively. As the results shown in figure 5, the galvanic corrosion currents at the initial stage were of the order of magnitude 10^{-4} A.cm^{-2}. As the time extends, the current finally decreased to the order of magnitude 10^{-8} A.cm^{-2}. This result exhibits similar trends to those observed in the case of the galvanic corrosion potentials (figure 4) and impedance (figure 3) result, further confirms that the galvanic corrosion between stainless steel

and carbon steel mainly existed in the initial stage, and the risk of galvanic corrosion will significantly decrease as the time extends.
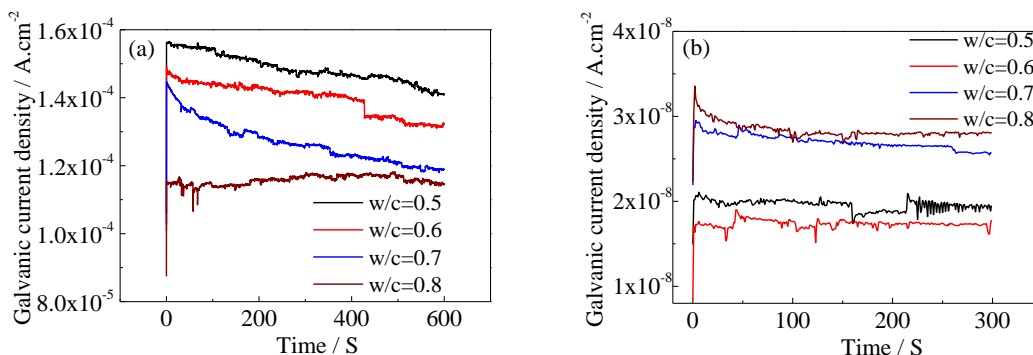

Figure. 5 Galvanic corrosion currents density of coupling stainless-carbon steel electrode in mortar in 5% NaCl solution. (a) 28 days, (b) 238 days.

The impedances of the carbon steel coupled with the stainless steel in the chloride contaminated mortars also have been tested at 28 days and 238 days, respectively. As figure 6 shows, the carbon steel sample coupling with stainless steel presents two capacitive loops (figure 6(a)) at the initial 28 days, and this situation is significantly different from the single carbon steel (figure 3(b)) immersed in mortars. Connection with the stainless steel promotes the passivation of the carbon steel and a passive film formed on the carbon steel after 28 days. Thus, a capacitive loop at high frequency existed in the Nyquist plots of the carbon steel at 28 days [11]. As the time extends to 238 days, the impedance values of carbon steel significantly higher than these in the initial stage. The radius of the capacitive loop obviously increased, which indicates that the carbon steel was further passivation. On the other hand, there is no significantly difference in impedance of the coupled carbon steel among various water-cement ratios mortars.
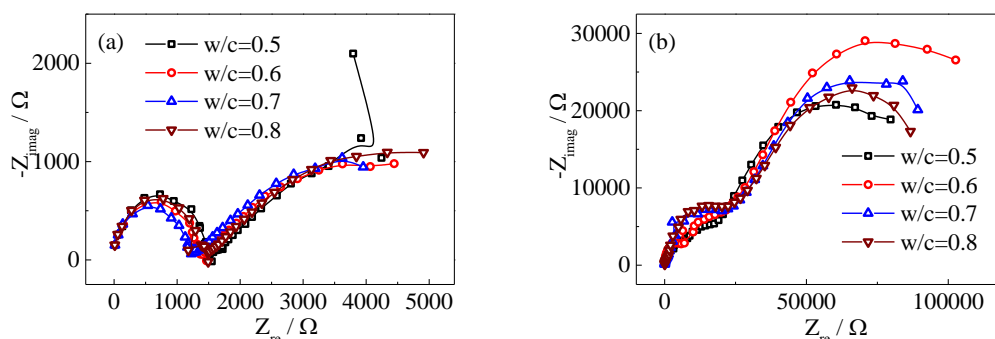

Figure. 6 Nyquist plots of carbon steel in coupling electrode in mortar in 5% NaCl solution. (a) 28 days, (b) 238 days.

3.3 Corrosion state of coupling stainless steel and carbon steel

Figure 7. Corrosion states of the coupled stainless-carbon steel sample after 238 days.

The corrosion state of the coupled stainless steel and carbon steel in the chloride-contaminated mortars was examined after removing the mortars cover layers at 238 days. As figure 7 shows, there is no visible corrosion onset on the carbon steel rebar even it was directly connected with the stainless steel and immersed in the chloride contaminated environment. Interesting, the galvanized iron wire are corroded in somewhere. This may be attributed to the plastic deformation of the wire during the tie process. Our earlier studies [12, 13] showed that the plastic deformation significantly increases the activity of carbon steel in concrete environment. Thus, the deformed carbon steel tie-wire is more easily corroded in the chloride contaminated mortars.

4. CONCLUSIONS

(1) The galvanic current of the coupled stainless steel and carbon steel is in order of 10^{-4} A.cm^{-2} in the initial stage. This situation suggests that a high galvanic corrosion risk on the carbon steel when it is coupled with stainless steel in the chloride-contaminated concrete.

(2) Connection with stainless steel promotes the passivation of carbon steel in mortars. After 238 days immersed in the mortars with chlorides, the galvanic current between the two steels is only in the order of 10^{-8} A.cm^{-2} and indicates that there is no practical risk of galvanic corrosion when carbon steel and stainless steel are electrically coupled in reinforced concrete structures.

(3) After immersed 238 days in the chloride contaminated mortars, obvious corrosion is observed on the galvanized iron wire, while no visible corrosion onset existed on the coupled stainless steel and carbon steel rebar. This result suggests that the galvanized iron wire is not suitable for tying the two steel in the chloride-contaminated concrete.

(4) The water-cement ration does no show significantly influence on the galvanic corrosion between stainless steel and carbon steel in the chloride-contaminated environment for long time.

References

1. W. Wang, J. Xu, G. Gao, L. Jiang, *Journal of Hohai University (Natural Sciences)*, 42 (2014) 535
2. J. Xu, H. Shan, L. Tang, G. Gao, L. Jiang, Y. Xu, *Journal of Hohai University (Natural Sciences)*,43 (2015) 489
3. L. Jiang, R. Liu, L. Mo, J. Xu, H. Chu, *Journal of Hohai University (Natural Sciences)*, 41 (2013) 32
4. P. Castro-Borges, O.T. de-Rincón,E.I. Moreno, A.A.Torres-Acosta, M. Martínez-Madrid, A. Knudsen, *Mater. Performance,* 41 (2002) 50
5. L. Bertolini, M. Gastaldi, M.P. Pedeferri, P. Pedeferri, T. Pastore, Proc. Int. Conf. on Corrosion and Rehabilitation of Reinforced Concrete Structures, Orlando, 1998: 7-11.
6. C.M. Abreu, M.J. Cristóbal, M.F. Montemor, X.R. Nóvoa, G. Pena, M.C. Pérez, *Electrochim. Acta,* 47 (2002) 2271
7. S. Qian, D. Qu, *J. Appl. Electrochem*., 40 (2010) 247
8. C.F. Dong, K. Xiao, X.G. Li, Y.F. Cheng, *Wear*, 270 (2010) 39
9. C.F. Dong, K. Xiao, X.G. Li, Y.F. Cheng, *J. Marer. Eng. Perform*, 20 (2011) 1631
10. J. T. Pérez-Quiroz, E. M. Alonso-Guzmán, W. Martínez-Molina, H. L. C. M. Rendón-Belmonte, M. Martínez-Madrid, *Int. J. Electrochem. Sci*., 9 (2014) 6734
11. D.V. Ribeiro, J.C.C. Abrantes, *Constr. Build. Mater*., 111 (2016) 98
12. X. Feng, X. Lu,Y. Zuo, D. Chen, *J. Brazil. Chem. Soc*., 25 (2014) 372
13. X. Feng, Y. Tang, Y. Zuo, X. Lu, *Corros. Sci*., 65 (2012) 542