Study on improvement of durability for reinforced concrete by surface-painting migrating corrosion inhibitor and engineering application

Ning Song 1, Zixiao WANG 1, Zhiyong LIU 1,3, Jiuyuan Zhou 2, Duo Zheng 2

1School of civil engineering, Yantai University, Yantai, Shandong 264005, China
2Jilin Province Institute of Water Conservancy Science Research, Changchun, Jilin 130000, China

Abstract. The corrosion currents of steel bar in concrete with three W/B and four chloride contents after surface-painting two migrating corrosion inhibitors (PCI-2015 and MCI-A) 14d to 150d in atmospheric condition were measured. The results showed that the corrosion current density ($I_{corr}$) of steel bar reduced to 0.1 μA.cm$^{-2}$ from the initial highest 3.833 μA.cm$^{-2}$ (W/B=0.65, NaCl-1%) after surface-painting PCI-2015 14 d, and the $I_{corr}$ was still lower than 0.1 μA.cm$^{-2}$ until 150d. The compressive strength and chloride migration coefficient of concrete specimens were tested. The possible reasons of the mechanisms of durability improvement for reinforced concrete by applying PCI-2015 inhibitor were PCI-2015 may be reacted with calcium hydroxide in cement concrete and lots of inhibitor particles may be adsorbed on the active sites first and then a stable protective layer may be formed. The $I_{corr}$ of steel bars in a hydraulic aqueduct concrete structure after painting PCI-2015, MCI-A (the United States) and MCI-B (Europe) during 6 months was monitored by Gecor 8 tester. The results showed that the average values of $I_{corr}$ of steel bars after painting the PCI-2015 150d fulfilled the specification requirements in “Design code for concrete structure strengthening (E.3)” (GB50367-2013).

1. Introduction

The corrosion of steel bars in concrete structures causing by chloride ions in marine environment and the areas using deicing salts is a main cause for early deterioration and short service life of concrete structures [1], which leads to huge economical losses. Large amounts of engineering practices showed that migration corrosion inhibitor (MCI) is an effective technique to delay and inhibit the corrosion of steel bar in concrete [2]. In recent years, some studies on MCI have been carried out, such as the anticorrosion performance and mechanism of MCI in chloride solution [3] and the anti-corrosion performance of MCI by surface-painted to concrete [4-5,10] and the transmission model of MCI in cement concrete [6-9]. The MCIs have been used in some experimental engineering projects. With the increase of the requirements for concrete structures’ durability repairing, MCI technique has gradually evolved into the principal method to improve the durability of structures.
2. Experimental

2.1. Materials and concrete mix proportion
Portland cement with the type of P.O.42.5R, river sand, stone with continuous grading between 5mm to 25mm, superplasticizer, fly ash with fineness of 20% and slag powder with the type of S95 were used in the test. Steel electrodes were made of Q235 steel with the size of $\phi 12 \text{ mm} \times 70 \text{ mm}$. The surface roughness of steel electrodes was not greater than 3.2$\mu$m. The auxiliary electrodes were stainless steel sheets with the size of 10 mm×70 mm. Concrete specimens (size of 100 mm×100 mm×100mm) were prepared with three water to binder ratios (W/B of 0.45, 0.55, 0.65) and four contents of NaCl (0%, 0.5%, 0.75% and 1% of binder weight), concrete mix proportion was shown in Table 1. Two steel electrodes and one auxiliary electrode block were placed in each cubic specimen. The concrete in 1#, 5# and 9# (in Table 1) were also designed to prepare the cylinder concrete specimens (size of $\phi 100 \text{ mm} \times 250 \text{ mm}$). All specimens were placed in the standard curing room till the age of 28 d. After curing, the cylinder concrete specimens were cut into slice with the size of $\phi 100 \times (50\pm 2) \text{ mm}$.

Table 1. Concrete mix proportion for 1m$^3$ (kg)

| number | W/B | water | cement | fly ash | slag | stone | sand | NaCl |
|--------|-----|-------|--------|---------|------|-------|------|------|
| 1#     | 0.45| 150   | 240    | 80      | 80   | 950   | 930  | 0.00 |
| 2#     | 0.45| 150   | 240    | 80      | 80   | 950   | 930  | 2.00 |
| 3#     | 0.45| 150   | 240    | 80      | 80   | 950   | 930  | 3.00 |
| 4#     | 0.45| 150   | 240    | 80      | 80   | 950   | 930  | 4.00 |
| 5#     | 0.55| 150   | 210    | 100     | 50   | 950   | 930  | 0.00 |
| 6#     | 0.55| 150   | 210    | 100     | 50   | 950   | 930  | 1.80 |
| 7#     | 0.55| 150   | 210    | 100     | 50   | 950   | 930  | 2.70 |
| 8#     | 0.55| 150   | 210    | 100     | 50   | 950   | 930  | 3.60 |
| 9#     | 0.65| 150   | 190    | 80      | 70   | 950   | 970  | 0.00 |
| 10#    | 0.65| 150   | 190    | 80      | 70   | 950   | 970  | 1.70 |
| 11#    | 0.65| 150   | 190    | 80      | 70   | 950   | 970  | 2.55 |
| 12#    | 0.65| 150   | 190    | 80      | 70   | 950   | 970  | 3.40 |

2.2. Test methods

2.2.1. Electrochemical tests
Linear potential resistance(LPR) of steel bars in cubic concrete specimens were tested by PARSTAT2273 electrochemical workstation. After curing, the initial LPR of the steel bars in cubic specimens were tested, and then these specimens dried in the oven at 50°C for 24 h. After the specimens cooling to room temperature, two kinds of MCIs (PCI -2015 and MCI-A) were surface-painted to the specimens. Finally the LPR of the steel bar was tested after painting for 14 d, 28 d and 150 d. The corrosion current density ($I_{corr}$) of steel bar could be calculated based on the value of LPR. In order to ensure the comparability of the results, the painting amounts of PCI-2015 and MCI-A were 200 g.m$^{-2}$.

2.2.2. Mechanical property and durability tests
Compressive strength of cubic specimens was tested based on the method in the national standard (GB/T50081-2002). Chloride migration coefficient of each specimen was tested by NTB-DAL type chloride diffusion coefficient tester and vacuum water retention system. The test method is according to the national standard (GBT50082-2009).
3. Results and discussion

3.1. Electrochemical properties

$I_{\text{corr}}$ of steel bars in the concrete (three water to binder ratios) was changing with time after painting MCIs, as seen in Figure 1 to Figure 3. The results showed that the anti-corrosion property of PCI-2015 was better than that of MCI-A under the same condition.

![Figure 1](image1)

**Figure 1.** Temporal variations of $I_{\text{corr}}$ of steel bars in the concrete after painting MCIs (W/B=0.45)

![Figure 2](image2)

**Figure 2.** Temporal variations of $I_{\text{corr}}$ of steel bars in the concrete after painting MCIs (W/B=0.55)

![Figure 3](image3)

**Figure 3.** Temporal variations of $I_{\text{corr}}$ of steel bars in the concrete after painting MCIs (W/B=0.65)

3.2. Mechanical property and durability

The compressive strength of concrete was shown in Figure 4. The compressive strength of concrete decreased with the increase of W/B ratio. When concrete specimens have the same water to binder ratio, the more the content of chlorine salt content, the higher the compressive strength. This might due to the amounts of calcium aluminate hydrate were higher in concrete with lower W/B ratios than that in higher W/B ratios, causing the porosity of concrete reduced and the density of the material improved.

The chloride diffusion coefficients of concrete specimens (three water to binder ratio) painting PCI-2015 and MCI-A were shown in Figure 5. Compared with the blank group, the enhancements of concrete to resist chloride penetration capability by painting PCI-2015 was better than that of painting MCI-A group.
3.3. Discussion
The above experimental results showed surface painting PCI-2015 can not only reduced the chloride diffusion coefficient of concrete but also inhibited the corrosion rate of steel in concrete. The possible reasons were as follows. First, the polycarboxylic acid in PCI-2015 may be reacted with calcium hydroxide in cement concrete [7], so plugging and hydrophobic effect was produced. So the penetration of oxygen, water and chloride ion is reduced. Second, when PCI-2015 was penetrated into the steel surface, lots of inhibitor particles may be adsorbed on the active sites first and then a stable protective layer may be formed, as a result the anodic and cathode reactions on the steel surface are hindered [11].

4. A case of engineering application
An aqueduct was built in 1970s at Hengdaohoe in Jilin province. Years later, concrete of aqueduct showed a large area of aging and erosion, and the reinforcements were partially uncovered in some areas. In 2013, two framed bents were collapsed by the flood, causing a serious dislocation of the aqueduct body. In order to improve the durability and prevent further corrosion of reinforcements in the aqueduct, surface-painting MCI was selected. Three kinds of MCI products (PCI-2015, MCI-A from USA and MCI-B from Europe) were selected to the repair the durability of the aqueduct. The electrochemical performance of reinforced bars in concrete was tested online by the Gecor 8 tester. Setting 60 testing points in each section of the aqueduct body, the LPR values of the steel bar in these points were tested before and after painting the MCIs. After painting MCIs 150d, the calculated average inhibition efficiency (IE) of the three inhibitors was 86.37% (PCI-2015), 48.85% (MCI-A) and 81.09% (MCI-B) respectively under the same conditions. Obviously the IE of using PCI-2015 on concrete of the aqueduct met the requirements of the national standard [12].

5. Conclusion
The corrosion currents of steel bar in concrete with three W/B and four chloride contents after surface-painting two organic corrosion inhibitors (PCI-2015 and MCI-A) 14d to 150d in atmospheric condition were measured. The results showed that the corrosion current density ($I_{corr}$) of steel bar reduced to 0.1 $\mu$A.cm$^{-2}$ from the initial highest 3.833 $\mu$A.cm$^{-2}$ (W/B=0.65, NaCl-1%) after surface-painting PCI-2015 14d, and the $I_{corr}$ was still lower than 0.1 $\mu$A.cm$^{-2}$ until 150d. The diffusion coefficient of chloride ion of concrete surface-painted PCI-2015 decreased by 28.57%, 38.36% and...
57.73%. The possible reasons of the mechanisms of durability improvement for reinforced concrete by applying PCI-2015 inhibitor were PCI-2015 may be reacted with calcium hydroxide in cement concrete and lots of inhibitor particles may be adsorbed on the active sites first and then a stable protective layer may be formed. The \( I_{\text{corr}} \) of steel bars in a hydraulic aqueduct concrete structure after painting PCI-2015, MCI-A and MCI-B during 6 months were monitored by Gecor 8 tester. The results showed that the average \( I_{\text{corr}} \) of steel bars after painting the PCI-2015 150d fulfilled the specification requirements in “Design code for concrete structure strengthening (E.3)” (GB50367-2013). In this way, the restoration project realized lower construction waste, energy saving and low carbon emission, which lead to remarkable social, economic and ecological benefits.

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