Environmental Influence on the Corrosion Rate of Steel Bars Embedded in Concrete

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Investigation was carried out to verify the influence of temperatures in an ambient environment on the corrosion rate of steel reinforcement in concrete structures. Two concrete specimens, into which from an upper surface 10% sodium chloride solution permeated, were exposed outdoors. To evaluate the corrosion rate of steel bars embedded in concrete, the macro-cell corrosion current and the polarization resistance were measured regularly for more than 4 years, employing the AC impedance measurement. The macro-cell corrosion current and the polarization resistance of steel bars embedded in concrete were highly affected by temperature. It is found that the corrosion rate has increases linearly as 1/10 times against 1°C rise in temperature.

KEY WORDS: macro-cell corrosion; AC impedance; temperature; polarization resistance; chloride ion.

1. Introduction

In the past several decades, corrosion problems of reinforced concrete structures by salt attack have been widely reported throughout the world. Not only reports regarding durability have been found, but also the economic impact has become a major concern.1–3) Conventionally, concrete is known to be sufficiently durable, because with high alkaline environment a passive film is formed on the surface of rebar. This protective film is destroyed when pH levels on the rebar are reduced by carbonation or chloride concentration reaches to the certain level due to ingress of chloride ions through concrete. A corrosion process occurs currents of steel bars and that cause serious cracks in RC structures due to the increase in corrosives with the passage of time. Thus, the check in structures in the early stage is required to avoid corrosion under such harmful conditions.4–8) The effect of chloride ions is more serious than that of carbonation.

The polarization resistance method based on AC impedances can be applied to evaluate the on-site corrosion rate of reinforced steel in concrete structures.9,10) Although the corrosion process is a chemical reaction influenced by temperature, the influence of temperature on the corrosion rate of steel bars embedded in concrete has not been precisely clarified.

In this research, for more than 4 years, the corrosion behavior of steel bars in reinforced concrete specimens exposed to outdoors has been studied. Temperature, the macro-cell corrosion current and the polarization resistance were measured periodically. In addition, the amount of corrosion estimated from the time integration of the polarization resistance is compared with the actual amount measured from gravimetric weight loss.

2. Experimental Procedure

2.1. Specimens and Exposure Conditions

In an exposure test, two reinforced concrete specimens were prepared. These are shown in Fig. 1. The deformed steel bar with a 13 mm diameter were used as steel bar A and B. Steel bar A and B were arranged at 20 mm and 40 mm cover-thickness respectively. The surface condition of a steel bar is clean. Macro-cell corrosion current is measured by the zero-shunt ammeter, connecting a steel bar A with a stainless steel bar (SUS304; austenitic stainless steel (Grade 304)) through the ammeter. Half-cell potential is measured by SRI-CM-3, connecting a steel bar B. Concrete was cast on Oct. 12, 1998. Mix proportion of concrete is given in Table 1. After 60-d curing process, four sides of each specimen were coated with epoxy resin. During the cure, the specimens were covered with 10 mm thicker clothes, and water was periodically poured on the top to keep them wet. After 60-d, the 10 mm thicker cotton clothes were put on the upper surface with tap water, or 10% sodium chloride solution, which was store on the upper surface. The two concrete specimens were then exposed to the outdoors according to the two conditions (Table 2).

2.2. Macro-cell Corrosion Current and Temperature

The macro-cell corrosion is normally caused by chloride-induced corrosion. The protected films on the steel surface
are destroyed by certain amounts of chloride. As a result, the corrosion forms corroded pits or holes on the steel surface in small anodic areas surrounded by relatively large areas of passive steel (acting as the cathode).\(^9,10\) Macro-cell corrosion current to know corrosion period is measured by the zero-shunt ammeter, connecting a steel bar A which is shown in Fig. 1 with a stainless steel bar through the ammeter. Changes in the macro-cell current were measured continuously from the start time of the outdoor exposure test. The outdoor temperature in the exposed area and the internal temperature of the concrete specimen were measured using thermocouples.

2.3. The Polarization Resistance

Polarization resistance was measured to estimate the micro-cell corrosion rate of steel bar B in Fig. 1. The polarization resistance of steel bar B was measured using a corrosion rate meter, SRI-CM-III. As shown in Fig. 2, the equipment is based on AC impedance method, using a three-electrode system. Concrete resistivity and the polarization resistance are measured by a central counter electrode. With the advantage of a double-disk counter electrode system,\(^11\) the guard electrode can confine the scattering of current within the central electrode. Half-cell potential is also measured.\(^12,13\)

For the measurement of the polarization resistance, a small sinusoidal voltage is applied, and the amplitude of sinusoidal current response and the phase difference between the two signals are measured. The apparent polarization resistance, \(R_{\text{ct}}\), is obtained from the AC impedance measurements at two frequencies of 10 Hz and 20 mHz. Then, the true polarization resistance, \(R_{\text{ct}}\), is defined by

\[
R_{\text{ct}} = R_{\text{ct}}^* \times S \quad \text{...(1)}
\]

where \(R_{\text{ct}}^*\) is the apparent polarization resistance, and \(S\) (=82 cm\(^2\)) is the surface area of a steel rebar. The polarization resistance is in inverse proportion to the corrosion current density, \(I_{\text{corr}}\), which is defined from the formula developed by Stern and Geary.\(^14\)

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Table 1. Mix proportion of concrete for specimens.

| W/C | S/a | Weight of unit volume (kg/m\(^3\)) | Slump | Air | Compressive Strength |
|-----|-----|-----------------------------------|-------|-----|---------------------|
| (%) | (%) | W | C | S | G | (cm) | (%) | (MPa) |
| 48  | 44.9| 172 | 359 | 762 | 952 | 15.6 | 5.8 | 27.9 |

* C: Ordinary Portland cement, S: Mixture of washed sea-sand and crushed sand, G: Crushed gravel

Table 2. Curing and exposure conditions.

| Curing time | Site   | Environmental Condition | Specimen No.1 | Specimen No.2 |
|-------------|--------|--------------------------|---------------|---------------|
| Until 60    | Indoors| wet-curing               |               |               |
| From 60 to 247 | Outdoors | Tap water | 10% sodium chloride solution |               |
| After 247   | Outdoors | 10% sodium chloride solution | 10% sodium chloride solution | |
where the value of $K$ is assumed to be 0.026 V.\(^{15}\)

After employing an exposure test for two months, the polarization resistance was measured once a month. According to CEB recommendations,\(^{16}\) the measured polarization resistance can be converted to the corrosion rate and the penetration depth per year as given in Table 3.

3. Results and Discussion

3.1. Temperature and Macro-cell Corrosion Current

Figure 3 shows the change in the external temperature at the site of exposure over 4 years and 4 months from Nov. 9, 1998 to Mar. 4, 2003. During the exposure test, the maximum temperature was 34°C and the minimum was 2°C.

Figure 4 shows the change in the macro-cell corrosion current of four steel bars A embedded in concrete specimens No. 1 and No. 2. The macro-cell corrosion current showed a rise during summer with high temperatures and a fall during winter with low temperatures. It is known that the chloride ion, supplied from the sodium chloride solution and stored on the upper surface of the concrete specimen, triggered the corrosion of the steel bars embedded in concrete. Table 4 shows the macro-cell corrosion current during the exposure test. Although the mix proportion of concrete specimens No. 1 is the same as specimen B, curing conditions are different as given Table 2. From Fig. 3, Fig. 4 and Table 4, the day when macro-cell corrosion began was evident, and that the maximum current value was influenced by the early curing conditions in addition to the concrete cover.

3.2. Micro-cell Corrosion Rate

Micro-cell corrosion is observed over the entire surface of steel in which the part between anodic and cathodic areas is similar.\(^{9,10}\) Anodic and cathodic areas are observed closely one another on the same bar.

Figure 5 shows the changes in the polarization resistances of four steel B bars embedded in concrete specimens No. 1 and No. 2. In the case that the micro-cell corrosion activities of these four steel B bars were estimated from the evaluation criteria for the polarization resistance measure-
ments shown in Table 3, three steel bars except the one (No. 1-4-B) with 4 cm concrete cover in specimen No. 1 could be corroded. Two steel bars (No. 2-2-B and No. 2-4-B) in specimen No. 2 seemed to be corroded before the polarization resistance measurements started. Steel bars with 2 cm cover in specimen No. 1 (No. 1-2-B), showed the corrosion after 2 years. Because of the polarization resistance decreased dramatically after 680 d of exposure.

Comparing Fig. 3 with Fig. 5, similar tendencies that the polarization resistance decreases with the rise in temperature and increases with the fall in temperature were observed. Since the polarization resistance is in inverse proportion to the corrosion rate, it is clear that the micro-cell corrosion rate of a steel bar increased with the rise in temperature.

Corrosion resulted by the sodium chloride solution, stored on the upper surface of the concrete specimen. This means that the corrosion rate increase with increasing the chloride content according to the position of a steel bar.

The effects of temperature on the polarization resistances of four steel bars B over 4 years are summarized in Fig. 6. In the logarithm scale, a negative correlation of the polarization resistance with the internal temperature is observed. The slope of the non-corroding steel bar (No. 1-4-B) was smaller than those of the other three bars corroded. Although the polarization resistances of the three corroded bars are different, the slopes are similar. Since the polarization resistance is in inverse proportion to the corrosion rate, this Figure also show that the corrosion rate of steel bar increases with the rise in temperature. In corroded bars, the polarization resistance at 30°C is approximately 0.25 times greater than that at 2°C. Thus, it is considered that at Shikoku Island in Japan, the corrosion rate of the corroding steel bar in summer is approximately estimated as 4.0 times high in winter.

3.3. Amount of Corrosion

After applying the exposure test for 1 400 d, a crack appeared evident on the concrete surface near steel bar (No. 2-2-B). After 1 620 d, the steel bar (No. 2-2-B) with 13 mm diameter and 20 cm length was taken out of the specimen with a concrete core sample should be explained into four sections as shown in Fig. 7. The actual amount of corrosion measured from gravimetric weight loss was 95.1 mg/cm² (average value of 4 sections) as listed in Table 5. The amount of corrosion estimated from the reciprocal of the polarization resistance was 162 mg/cm² as shown in Table 6. Therefore, the amount of corrosion estimated from the polarization resistance (162 mg/cm²) is 1.7 times of the actual amount of corrosion (95.1 mg/cm²). It was confirmed that the amount of corro-
4. Conclusion

For more than 4 years, the corrosion behavior of steel bars in reinforced concrete specimens exposed to outdoors has been studied. Temperature, the macro-cell corrosion current and the polarization resistance were measured periodically. In addition, the amount of corrosion estimated from the time integration of the polarization resistance is compared with the actual amount measured from gravimetric weight loss. Results obtained are summarized, as follows:

(1) The macro-cell corrosion current and the polarization resistance of steel bars in concrete were greatly affected by the temperature at the time of measuring, in addition to the concrete cover, the early curing condition, and the chloride content.

(2) The macro-cell corrosion current and the polarization resistance of steel bars embedded in concrete were highly affected by temperature. It is found that the corrosion rate has increases linearly as 1/10 times against 1°C rise in temperature.

(3) The amount of corrosion estimated from the polarization resistance (162 mg/cm²) is 1.7 times of the actual amount of corrosion (95.1 mg/cm²). It was confirmed that the amount of corrosion could be estimated from the regularly measured integration of the polarization resistance.

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Table 5. Actual amount of corrosion measured from gravimetric weight loss.

| Section | Rate of corrosion area (%) | Actual amount of corrosion (mg/cm²) |
|---------|---------------------------|-----------------------------------|
| 1       | 17.5                      | 20.8                              |
| 2       | 32.0                      | 81.5                              |
| 3       | 42.2                      | 115.8                             |
| 4       | 57.8                      | 162.4                             |
| Average |                          | 95.1                              |

* A crack was observed after 1400 days in the exposure test

Table 6. Amount of corrosion and corrosion rate estimated from polarization resistance.

| Time (days) | Estimated polarization resistance (mg/cm²) | Ratio | Average corrosion rate (mg/cm²/year) |
|------------|-------------------------------------------|-------|--------------------------------------|
| 0 to 170   | 0                                         | 0.000 | 0.0                                  |
| 0 to 1400  | 106                                       | 0.654 | 31.4                                 |
| 0 to 1620  | 162                                       | 1.000 | 92.9                                 |

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