Measurement Method for Macrocell Corrosion in Concrete Specimen using a Segmented Steel Bar
Shinichi Miyazato1* and Nobuaki Otsuki2

Abstract
Regarding the spatial distribution of the corrosion process it is important to distinguish between macrocells and microcells, and to measure them quantitatively when experimentally clarifying the mechanism of corrosion of steel reinforcement embedded in concrete to decide an appropriate countermeasures. Therefore, this study is aimed to develop a method for measuring macrocell and microcell currents while dividing the rebar embedded in a concrete specimen into segments. The macrocell current is defined as the current flowing between rebar segments, whereas the microcell current flows within a single segment. First, it can be confirmed that the segment length does not influence the magnitude of the total corrosion current, which is the total of the macrocell anodic current and the microcell current. In addition, it can be confirmed that the magnitude of the macrocell current increases as the segment length decreases. From the experimental results obtained, the magnitude of the macrocell anodic current or the microcell current became constant when the length of individual segments was 15 mm or less. Also, the measured value of the macrocell current flowing between the neighboring segments could evaluate the macrocell current flowing between all elements. Additionally, the amount of steel loss derived from the corrosion current using electrical measurement methods became equal to the total corrosion weight loss.

1. Introduction
A reinforced concrete structure should continue performing its intended functions during its full design service life. A significant amount of attention has been and is still being paid to the durability of concrete, and several researches have been executed with this in mind. When a reinforcing steel bar is corroding, either due to chloride attack or due to carbonation, the rate of degradation is generally fast. Therefore, it is considered necessary to clarify the underlying mechanisms of the corrosion process for both chloride attack and carbonation. The size of the corroding area, weight loss, and corrosion pit depth were measured experimentally by standard tests, such as ISO 21062, JCI-SC1, and proposed in literature (Chen 2020; Mohammed 2015). However, because it was difficult to completely remove the rust and the difference in the mass before and after the corrosion was small under a short test period, the precision was low.

Corrosion of steel rebars in concrete can be classified into two types based on the spatial configuration of the electrochemical cell. The first type is referred to as a macrocell corrosion and for this type of corrosion anodic steel areas (Fe → Fe2+ + 2e−) can be clearly distinguished from cathodic steel areas (O2 + 2H2O + 4e− → 4OH−). Macrocell corrosion occurs when the chloride ion concentration or pH strongly varies along a steel rebar. The other type is termed microcell corrosion, where microscopic anodic and cathodic areas are randomly dispersed over the steel surface and coexist within close proximity. Both microcell and macrocell activity simultaneously contribute to the overall corrosion process. In particular, it is reported that the macrocell corrosion often occurs around the crack of an existing structure and around a patch-repair part. Moreover, this progress is known to be fast and dangerous empirically (Qiao 2016). Therefore, it is necessary to distinguish microcell corrosion from macrocell corrosion to evaluate rebar corrosion in concrete.

Despite measuring the half-cell potential to evaluate the potential difference between the anode and cathode (Kawahigashi 2003; Maruya 2007; Hussain 2011; Paul 2014), a qualitative assessment should be applied for macrocells. Furthermore, it is important to distinguish between macrocells and microcells, as well as to measure them quantitatively to clarify the corrosion rate and to propose a suitable countermeasure method. Table 1 shows examples of experiments, which were distinguished the macrocell corrosion rate from the microcell corrosion rate. In these studies, segmented steel elements were embedded in a concrete specimen. However, not only there is no standardized test method, but also the unified experimental method is not considered. For example, in order to compare the measurement results of different experiments, the corrosion current density per unit area is used as an index. Here, when the density was calculated, the standard length of the segmented...
steel bar must be determined. Unfortunately, the standard length of a segmented steel bar is not taken into account. This situation is like comparison for the compressive strength of concrete using cylinder and cubic with different sizes. Furthermore, the amount of steel lost due to corrosion is important in assessing the load capacity of the member. This corrosion loss would theoretically be calculated from the cumulative magnitude of electrons produced by the anodic reaction. Here, the correctness of this theory should be confirmed experimentally. That is, it is important to compare the result using segmented steel element with a result of past weight loss and to verify the result of measurement of a corrosion current by a segmented steel bar. However, this has not been confirmed yet.

Based on the above background, this study originally establishes a method for measuring macrocell and microcell currents using a segmented rebar embedded in a concrete specimen. Therefore, the length of the segmented steel bar is clarified for accurate measurement of macrocell and microcell current densities. Also the suitable location of a zero-resistance ammeter for measuring macrocell current is clarified. In addition, it has been confirmed that the corrosion current density measured using the segmented steel bar is equivalent to the corrosion weight loss.

2. Definition of macrocell and microcell corrosions

In this study, a single rebar is divided into a number of consecutive segments having a length of several centimeters. The corrosion cell that extends to the segment that differs from an anode to a cathode is defined as a macrocell. Therefore, a macrocell current is the electric current that flows between different segments. Meanwhile, the corrosion cell in which an anode and a cathode exist in a single element is defined as a microcell. Therefore, a microcell current is an electric current that flows within a segment. Here, if the length of the segment is quite long, the current inside the segment may be different from the strict microcell current described in Section 1. However, this has not been confirmed yet.

Table 1 Literature survey using segmented rebar.

| Author            | Year    | Theme                                                   | Element length (mm) |
|-------------------|---------|---------------------------------------------------------|---------------------|
| Suzuki K., et al. | 1990    | Influence of anode/cathode area on macrocell corrosion  | 38, 50, 150, 350    |
| Schissl P., et al.| 1994    | Macrocell corrosion after patch repair                   | 80, 100             |
| Otsuki N., et al. | 2000    | Macrocell corrosion at bending crack                     | 45, 60, 135, 160    |
| Mohammed, T. U. et al. | 2001a  | Influence of shape on macrocell corrosion                | 50                  |
| Mohammed, T. U. et al. | 2001b  | Influence of crack width on macrocell corrosion         | 45                  |
| Mohammed, T. U. et al. | 2002  | Influence of gap at stirrup-concrete interface on macrocell corrosion | 30, 35, 80 |
| Nishida T., et al. | 2003    | Macrocell corrosion at column with joint under carbonation | 5, 10, 50, 100, 250 |
| Subramaniam K. & Bi M. | 2006  | Macrocell corrosion at crack                            | 51, 533             |
| Watanabe H., et al. | 2009   | Macrocell corrosion mechanism                           | 100, 300            |
| Otsuki N., et al. | 2009    | Influence of temperature on macrocell corrosion         | 3, 50, 100, 500     |
| Nanayakkara O. & Kato Y. | 2009   | Macrocell corrosion under non-homogeneous environment   | 15, 30, 45, 68      |
| Miyazato S. & Otsuki N. | 2010  | Macrocell corrosion at bending crack and joint           | 5, 10, 20, 30       |
| Miyazato S. & Hiraishi Y. | 2013  | Steel corrosion in HPFRC                                | 15                  |
| Takaya S., et al. | 2014    | Repair effect of lithium nitride injection method       | 20, 50, 110         |
| Raupach M. & Büttner T. | 2014  | Macrocell corrosion at bending crack                     | 20, 75              |
| Yamamoto M., et al. | 2018  | Repair effect of electric protection                     | 100                 |
| Gu X., et al.    | 2018    | Macrocell corrosion at intersection zones of steel rebar mesh | 25                  |
| Choe H., et al.  | 2019    | Anti-corrosion behavior of galvanized steel rebar        | 9.5                 |
| Sandra N., et al. | 2019   | Influence of bleeding on macrocell corrosion            | 100                 |
| Miyazato, S. & Hanaoka D. | 2020  | Countermeasure for re-corrosion after patch repair       | 20, 30, 40, 60, 70  |
| Yoshida T., et al. | 2021   | Cathodic protection with sacrificial zinc anode         | 115, 130, 175       |

2. Definition of macrocell and microcell corrosions

In this study, a single rebar is divided into a number of consecutive segments having a length of several centimeters. The corrosion cell that extends to the segment that differs from an anode to a cathode is defined as a macrocell. Therefore, a macrocell current is the electric current that flows between different segments. Meanwhile, the corrosion cell in which an anode and a cathode exist in a single element is defined as a microcell. Therefore, a microcell current is an electric current that flows within a segment. Here, if the length of the segment is quite long, the current inside the segment may be different from the strict microcell current described in Section 1. However, it must be noted that in this paper, the terms of not inner and outer currents but microcell and macrocell currents are used to avoid confusion for the experimenter due to the definition of multiple terms.

Figure 1 shows all corrosion cells in which the center segment becomes an overall anode where the anodic reactions dominate. This is an ideal situation so that only one anode is located the center segment. The cathode may exist in a segment itself as well as in all other segments, as shown in this figure. The former is a microcell, while the latter is a macrocell. Therefore, the

diagram shows all corrosion cells in which the center segment becomes an overall anode where the anodic reactions dominate. This is an ideal situation so that only one anode is located the center segment. The cathode may exist in a segment itself as well as in all other segments, as shown in this figure. The former is a microcell, while the latter is a macrocell.
summation of the microcell current produced within a single segment and all macrocell currents becomes the total corrosion current when an arbitrary element is an anode element.

3. Theoretical examination

Figure 2 shows the steel bars consisting of two or four segments, and the macrocell and microcell currents that flow between them. The length of each segment of a divided steel bar is 2a or a, respectively. The left side from the centerline is referred to as Area-L; conversely, the right side is referred to as Area-R. This section explains the relation between the macrocell, microcell, and total corrosion currents.

Here, it is assumed that the amount of chloride ions, oxygen, and moisture supplied to a steel bar with an equivalent surface area are the same regardless of the length of the segments. Therefore, it can be perceived that for Area-L, the amount supplied to segment A1 having a length 2a is equal to the summation of the amounts supplied to segments B1 and B2 when the length of each segment is equal to a. Similarly, the amount supplied to element A2 is equal to the summation of the amounts supplied to segments B3 and B4 in Area-R. Thus, the corrosion current of segment A1 and the corrosion current that combines segments B1 and B2 should be equal. Therefore, equation (1) may be obtained. Similarly, the corrosion current of segment A2 and that of the combination of segments B3 and B4 should be equal. Thus, equation (2) may be obtained. Furthermore, the corrosion current flowing between Area-L and Area-R should be equal. Therefore, equation (3) may be obtained. Here, all corrosion currents show absolute values which is the anode current.

\[ \text{MICRO}_{A1} = \text{MICRO}_{B1} + \text{MICRO}_{B2} + \text{MACRO}_{A12} \quad (1) \]

\[ \text{MICRO}_{A2} = \text{MICRO}_{B3} + \text{MICRO}_{B4} + \text{MACRO}_{A34} \quad (2) \]

\[ \text{MACRO}_{A12} = \text{MACRO}_{B13} + \text{MACRO}_{B14} + \text{MACRO}_{B23} + \text{MACRO}_{B24} \quad (3) \]

According to Fig. 2, when the segment length is 2a, the macrocell current is only MACRO_{A12}. On the other hand, when the segment length is a, the macrocell currents are MACRO_{B12}, MACRO_{B13}, MACRO_{B14}, MACRO_{B23}, MACRO_{B24}, and MACRO_{B34}. Comparing each of them based on equation (3), equation (4) may be obtained. Therefore, it was confirmed that the summation of the macrocell currents when the segment is short is larger than that when it is long.

\[ \text{MACRO}_{A12} < \text{MACRO}_{B12} + \text{MACRO}_{B13} + \text{MACRO}_{B14} + \text{MACRO}_{B23} + \text{MACRO}_{B24} + \text{MACRO}_{B34} \quad (4) \]

Next, the summation of the left sides in equations (1) and (2) should be equal to the summation of the right sides in them. Therefore, equation (5) may be obtained.

\[ \text{MICRO}_{A1} + \text{MICRO}_{A2} = \text{MICRO}_{B1} + \text{MICRO}_{B2} + \text{MICRO}_{B3} + \text{MICRO}_{B4} + \text{MACRO}_{B12} + \text{MACRO}_{B13} + \text{MACRO}_{B14} + \text{MACRO}_{B23} + \text{MACRO}_{B24} + \text{MACRO}_{B34} \quad (5) \]

According to Fig. 2, when the segment length is 2a, the microcell currents are MICRO_{A1} and MICRO_{A2}. On the other hand, when the segment length is a, the microcell currents are MICRO_{B1}, MICRO_{B2}, MICRO_{B3} and MICRO_{B4}. Comparing each of them based on equation (5), equation (6) may be obtained. Therefore, it was confirmed that the summation of the microcell currents when the segment is long is larger than that when it is short.

\[ \text{MICRO}_{A1} + \text{MICRO}_{A2} < \text{MICRO}_{B1} + \text{MICRO}_{B2} + \text{MICRO}_{B3} + \text{MICRO}_{B4} \quad (6) \]

Note: MACRO_{A12} denotes the macrocell current between A1 and A2 elements. In contrast, MICRO_{A1} indicates the microcell current in A1 element.

Fig. 2 Relation of macrocell and microcell currents when the length of both segments is 2a and the length of each of four segments is a.
In addition, the total corrosion current, which includes the added macrocell and microcell currents, becomes equivalent regardless of the length of the segment, as shown in equation (7).

\[
MICRO_{a1} + MICRO_{a2} > MICRO_{b1} + MICRO_{b2} + MICRO_{b3} + MICRO_{b4}
\]  \tag{6}

In addition, the total corrosion current, which includes the added macrocell and microcell currents, becomes equivalent regardless of the length of the segment, as shown in equation (7).

\[
MICRO_{a1} + MICRO_{a2} + MACRO_{a2} = MICRO_{b1} + MICRO_{b2} + MICRO_{b3} + MICRO_{b4} + MACRO_{a2} + MACRO_{a3} + MACRO_{a4} + MACRO_{b4}
\]  \tag{7}

In this study, the macrocell current flows between the segments, whereas the microcell current flows within a single segment after the steel bar has been subdivided into segments. Here, according to this section, the summation of the macrocell current increases as the segment length becomes short, while the summation of the microcell current increases as the segment length increases, as shown in Table 2. Therefore, using shorter segments makes measurement of a total corrosion current more accurate, with zero-resistance ammeter. Also, it can be confirmed that the segment length does not influence the summation of the total corrosion current at all segments. Here an infinitely long segment corresponds to a normal unsegmented rebar. Therefore, it can be considered that the summation of the total corrosion current of the experiment that used segmented steels is the same as the summation of the total corrosion current of an actual structure.

4. Experimental examination

4.1 Manufacture of a segmented steel bar

The procedure for making a segmented steel embedded in a concrete specimen is explained. Figure 3 shows the configuration of the rebar comprising a number of segments. A lead wire is soldered to both ends of the steel that is cut into appropriate length. Thereafter, two segments are insulated and connected with the epoxy resin to fix the shape. If a lead wire on the approaching side of a neighboring segment is joined, the steel will electrically act as one rebar.

The measurement of the macrocell current that flows between the segments of a rebar became possible by embedding the divided bar in a concrete specimen. That is, the electric current between neighboring segments does not flow inside the rebar, but through an external ammeter, as shown in Fig. 4. Thus, it was possible to measure the macrocell current.

4.2 Method for measuring macrocell and microcell currents

In this section, the method for measuring the corrosion currents is examined when a specimen with segmented steel bars is used. Here, it should be noted that the lead wire that connects two elements is cut immediately when a microcell current is measured. Therefore, the corrosion cell in which an electrochemical balance was maintained is disturbed after this cut. Therefore, the order of the measuring electric current must be that a

![Fig. 3 Configuration of rebar composed of segmented steels.](image)

It is impossible to measure electric current in rebar.

![Fig. 4 Difference of normal continuous rebar and segmented steel bars.](image)
macrocell current is measured first and then followed by the microcell current under the usual condition.

(1) Measuring method of macrocell current
The macrocell current that flows through a lead wire between neighboring segments is measured with a zero-resistance ammeter. Simply, the lead wire connected during an exposure is cut after a zero-resistance ammeter is connected as a bypass circuit, as shown in Fig. 5. In addition, one zero-resistance ammeter is not connected in turn between elements, as shown in Fig. 6, and some zero-resistance ammeters are connected between all target segments simultaneously. Thereafter, the electric current that passes in both ends of a target segment is summed. Because this electric current is removed at the surface area of the segment, the macrocell current densities by the surface of the segment are calculated. For example, the macrocell current density \( a_i \) of segment-\( i \) shown in Fig. 7 may be calculated using equation (8).

\[
a_i = \frac{A_{i+1,i} + A_{i,i-1}}{S_i}
\]  

(8)

where, \( S_i \) means surface area of segment-\( i \) (mm\(^2\)).

When a target segment is an anode, the macrocell current densities are positive. Conversely, when a target segment is a cathode, the macrocell current densities are negative.

(2) Measuring method of microcell current
The measuring method of a microcell current is examined using existing literature sources (Stern 1957; Tsuru 1979; Kobayashi 2001; Itagaki 2012; Katayama 2014; Paul 2018; Andrade 2019; Suryanto 2020).

The Butler–Volmer equation is a basic expression for all electrode reactions. It is applied in the corrosion reaction of a rebar in concrete. Equation (9) shows the anodic portion of the Butler–Volmer equation.
where $\beta$ is the symmetry factor, which is set at 0.5. In addition, $i_i$ indicates the anodic current without external polarization (A), $R$ is the gas constant, $T$ is the absolute temperature (K), $F$ is the Faraday constant, $i$ is the polarization current (A), and $\eta$ is the overvoltage (V).

If an overvoltage is $\Delta \eta$ when a potential is $\eta_0$, and the electric current change caused by the overvoltage is $i_i$, then $\eta = \eta_0 - \Delta \eta$ and $i = i_i + \Delta i'$. Thus, substituting in equation (9), equation (10) is obtained.

$$i = i_i + \Delta i' = i_i \exp \left[ -\frac{\beta F \eta}{RT} \right]$$

Here, when $i_i \exp \left( -\frac{\beta F \eta_0}{RT} \right) = A$, equation (9) becomes equation (11).

$$i = i_i + \Delta i' = A \cdot \exp \left( \frac{0.5F \Delta \eta}{RT} \right)$$

The McLaughlin expansion applies to the right side of equation (11). Because the electric potential difference between the anode and cathode is small in a microcell, then $\frac{-RT}{0.5F} \ll \Delta \eta \ll \frac{RT}{0.5F}$. Therefore, it is possible to ignore third or more items with a small degree on the right side after McLaughlin expansion; thus, equation (11) result in equation (12).

$$i_i + \Delta i' = A \left( 1 + \frac{0.5F}{RT} \Delta \eta \right) = A + A \frac{0.5F}{RT} \Delta \eta$$

After a variable is separated from a fixed number, $i_i$ and $\Delta i'$ are calculated.

$$i_i = A = i_i \exp \left( -\frac{0.5F \eta_0}{RT} \right)$$

$$\Delta i' = A \frac{0.5F}{RT} \Delta \eta = i_i \exp \left( -\frac{0.5F \eta_0}{RT} \right) \frac{0.5F}{RT} \Delta \eta$$

The relationship between the polarization resistance $R_p$, polarization current $\Delta i'$ and overvoltage $\Delta \eta$ are shown in equation (15).

$$\Delta \eta = R_p \cdot \Delta i'$$

If equations (14) and (15) are compared, the relationship between the polarization resistance and corrosion current is obtained, as shown in equation (16).

$$\frac{\Delta i'}{\Delta \eta} = \frac{1}{R_p} = i_i \exp \left( -\frac{0.5F \eta_0}{RT} \right) \frac{0.5F}{RT}$$

Therefore, a microcell current is calculated by equation (17).

$$i_0 = \frac{RT}{0.5F} \frac{1}{\exp \left( -\frac{0.5F \eta_0}{RT} \right)} \frac{1}{R_p}$$

Equation (17) is written as equation (18), if $\frac{RT}{0.5F} \frac{1}{\exp \left( -\frac{0.5F \eta_0}{RT} \right)} = K$.

$$i_0 = \frac{K}{R_p}$$

The microcell current can be measured by the method based on equation (18). That is, a lead wire is cut to lose the electric current that flows from a different segment at first. Next, the polarization resistance of the surface of a target segment is determined by an alternating current impedance method that uses a Frequency Response Analyzer (FRA). The duration of cutting of lead wires before measuring polarization resistance is around a few hours. Figure 8 shows the test arrangement. A frequency is set from 5 mHz to 5 kHz, and an amplitude of 50 mV is imposed. In addition, the polarization resistance is calculated using the Bode diagram and Nyquist diagram. The microcell current density ($b_i$) of segment-i is calculated using equation (19).

$$b_i = \frac{K}{R_{p_i} \times S_i}$$

where $R_{p_i}$ is the polarization resistance ($\Omega$) of segment-i. Furthermore, $K$ is set to 0.0209 (V) as proposed by
(Tsuru 1979) who investigated local corrosion. This K value may differ depending on the corroded steel or passive steel, but it was set to be constant in this paper. The anodic current is equal to the cathode current in the target segment. Therefore, in this study, only the anodic current density is displayed as a positive value.

4.3 Procedure adopted for the production of specimens

Figure 9 shows a mortar specimen. The water-cement ratio of the mortar was 0.50. Moreover, a normal Portland cement and smooth cylindrical steel bar (SR295) with a diameter of 9 mm were used. The number of segments of a steel bar was set to 5 levels as 3, 5, 7, 11, and 23, using unit lengths of the segments of 65, 35, 25, 15, and 5 mm, respectively.

The above steel bar, as shown in 4.1, was placed in the center of a mold. The mold was divided in 2 neighboring sections to create a defective joint halfway the length of a specimen, and mortar was cast. The first mortar was cast until half of the mold was 200 mm in height. A laitance on the top surface was removed 24 h later, and the second mortar was cast into the upper layer. The specimen was cured in wet air with a relative humidity of 80% and temperature of 20°C for 27 d. Thereafter, an epoxy coating was applied on both the top and bottom surfaces to prevent the penetration of chloride ions and oxygen. As a result, they can penetrate only from the side surface of a constant cover depth. The specimen was then exposed for 56 d to an aggressive chloride-laden environment with repetition of a saltwater spray (NaCl 3.1wt%) for 24 h and a dryness (50% relative humidity) for 24 h. The room temperature was maintained at 20°C.

4.4 Experimental result

Figure 10 shows macrocell and microcell current densities determined for segments having a length 35 mm. It can be confirmed that both current densities are measured according to this figure.

Figure 11 shows the influence of the segment length on the corrosion current. The vertical axis shows the summation of the macrocell anodic current and the microcell current measured in all segments of each case. In addition, the total corrosion current, that is, the sum of macrocell anodic and microcell currents, is also shown. According to this figure, it can be confirmed that the summation of a total corrosion current was constant regardless of the segment length. In addition, it can be recognized that when the segments were short, the
summation of a macrocell anodic current was increased and the summation of the microcell current decreases. These are supported by the influence of segment length theoretically derived in Section 3.

As explained in Section 1, the anode and cathode are formed at different locations in macrocell corrosion. In particular, according to Table 1, it is pointed out that the corrosion rate at a crack and after a patch repair of concrete is affected by macrocell. Therefore, it is important to locate the anode in the macrocell and to measure the value of the macrocell current. Here, Fig. 11 describes that the value of a macrocell anodic current or a microcell current becomes same when the segment length is 15 mm or less. Therefore, based on Fig. 12, it is proposed that the steel bar with an segment length of 15 mm or less is used when evaluating corrosion by distinguishing between the macrocell and the microcell.

5. Macrocell corrosion current and location of zero-resistance ammeter

5.1 Experimental procedure

In this section, the currents flowing between all the segments were measured, and all macrocell currents were analyzed. The specimen is shown in Fig. 13. Six segments with the length of 1.5 cm were embedded in mortar with the water-cement ratio of 0.50. The preparing method is the same as in Section 4. However, the mortar on the only left side had chloride ions of 15 kg/m³. After 28 days of moisture curing, fifteen zero-resistance ammeters were connected between every segments to directly measure all macrocell currents. Finally the measurement method as shown in Fig 6 (1) was adopted with five zero-resistance ammeters.
5.2 Experimental result

The measurement results are shown in Table 3 and Fig. 14. Based on these values, Fig. 15 shows the macrocell current flowing into segment I, using the values measured by zero-resistance ammeters installed between segment I and the other five segments. According to this figure, between segments I and II, the macrocell current flowing from segment II to I is 0.092 μA. Therefore, segment I generates an electron accompanying the anodic reaction, while segment II receives this electron and consumes by the cathode reaction. Further, between segments I and III, because the macrocell current flowing from segment I to III is 0.847 μA, segment III is an anode and segment I is a cathode. Next, between segments I and IV, because the macrocell current flowing from segment IV to I is 0.704 μA, segment I is an anode and segment IV is a cathode. Next, between segments I and V, because the macrocell current flowing from segment I to V is 0.061 μA, segment V is an anode and segment I is a cathode. Finally, between segments I and VI, because the macrocell current flowing from segment VI to I is 0.102 μA, segment I is an anode and segment VI is a cathode. Based on these evaluations, it is recognized that segment I was the anode in the macrocells with segments II, IV and VI, while segment I was the cathode in the macrocells with segments III and V.

Similarly, the macrocell currents flowing into segments II to VI are shown in Figs. 16 to 20. According to these figures, the values of the macrocell currents flowing in from the remaining five segments change positively and negatively in any of the segments. Also it can be confirmed that there was no relationship between the distance and the absolute value of the macrocell current. That is, it cannot be judged that the farther the distance was, the less the macrocell current. From this, it is considered that the formation of macrocells was more strongly influenced by the corrosive environment around the two segments than the influence of the increase in electrical resistance due to the long distance between the anode and cathode. That is, it is clarified that if the corrosive environment of both segments was different at a distance of about 10 cm, the easily corrosive segment became an anode and a macrocell was formed.

Here, according to Fig. 14, the sum of the currents flowing into segments I to VI become -0.010 μA, -0.035 μA, 0.062 μA, -0.008 μA, -0.007 μA and 0.002 μA as shown in equations (20) to (25). Here, as in the experiment in Section 4, Fig. 21 shows the macrocell current

| Segment of cathode | I    | II   | III  | IV   | V    | VI   |
|--------------------|------|------|------|------|------|------|
| I                  | 0.092| -0.847| 0.704| -0.061| 0.102|      |
| II                 | -0.092| 0.097| -0.087| 0.002| 0.045|      |
| III                | 0.847| -0.097| -0.295| -0.469| 0.075|      |
| IV                 | -0.704| 0.087| 0.295| 0.274| 0.040|      |
| V                  | 0.061| -0.002| 0.469| -0.274| -0.261|      |
| VI                 | -0.102| -0.045| -0.075| -0.040| 0.261|      |

Table 3 Macrocell current measured by installing zero-resistance ammeters between all segments.

Fig. 14 Macrocell current measured by installing zero-resistance ammeters between all segments.
measured by installing zero-resistance ammeter only between neighboring segments. When the values of macrocell current shown in Fig. 21 compare with the values of equations (20) to (25), it is found that those values were equivalent. In addition, segment III, which has a positive value, becomes an anode of all six segments, while the remaining five segments, which have negative values, become cathodes. Therefore, it is confirmed that the current of the macrocell formed between each segment could be measured by installing a zero-resistance ammeter between neighboring segments as shown in Section 4.

\[
-0.010 - 0.044 + 0.019 + 0.011 + 0.003 = -0.010 \quad (20)
\]

\[
-0.092 + 0.097 - 0.087 + 0.002 + 0.045 = -0.035 \quad (21)
\]

Fig. 15 Macrocell current flowing into segment I.

Fig. 16 Macrocell current flowing into segment II.

Fig. 17 Macrocell current flowing into segment III.

Fig. 18 Macrocell current flowing into segment IV.

Fig. 19 Macrocell current flowing into segment V.

Fig. 20 Macrocell current flowing into segment VI.

Fig. 21 Macrocell current measured by installing zero-resistance ammeter only between neighboring segments which is methods in Section 4.
6. Corrosion current and weight loss at segmented steel bar

6.1 Making procedure of specimen

Figure 22 shows a mortar specimen. A normal Portland cement, smooth cylindrical steel bar (SR295) of ø9 mm, and deformed steel bar (SD295) of D10 mm were used. The water cement ratios of the mortar were 0.30 and 0.50. Seven steel segments each having a length of 4.5 cm were electrically connected. An epoxy-coated rebar was embedded in parallel with the segmented steel bar. The role of this epoxy-coated rebar was to withstand the load and to prevent the destruction of the segmented steel bar when the mortar specimen was bent. After the mortar was cast, the specimen was cured in a wet environment with 80% relative humidity and a temperature of 20°C. A crack was introduced at the underside a specimen halfway its length by bending with one loading point and two supports. In addition, as the chloride ions penetrated the specimen only from one side, an epoxy coating was applied on the mortar surface except for a crack occurrence surface. Thereafter, the specimen was exposed for 91 d to an aggressive chloride-laden environment by exposure to salt water splay (NaCl 3.1wt%, 1 ml/cm²/min) for 24 h alternated with exposure to dry air (50% relative humidity) for 60 h. In addition, the temperature was maintained at 60°C to promote a significant corrosion reaction.

Table 4 shows experimental cases. A level was set as the existence of a crack, type of the steel shape, water cement ratio of mortar and crack width. All six cases were compared.

6.2 Measuring method

The macrocell and microcell currents were measured, and the total corrosion current was calculated. Additionally, the total corrosion current determined at 7, 14, 28 and 91 days was integrated, and the corrosion quantity density for the exposure duration of all 91 d was calculated, as shown in the diagonal area in Fig. 23.

Furthermore, weight loss was measured. The steel bar was removed from a specimen after the mortar was split, and the rust was dissolved with 10% diammonium hydrogen citrate acid for 24 h under JCI-SC1. Thereafter, the deposit on the steel surface was removed completely using a sandpaper and wire brush, and then the steel bar was weighed with an accuracy of x mg. The difference between this weight and the initial weight without the acid dissolving of a steel bar before mortar casting was calculated as a corrosion weight loss. Moreover, the weight loss per unit of steel area was obtained by dividing the weight loss by the exposed surface area of the steel segment.

Table 4 Experimental case.

| W/C | Crack width (mm) |
|-----|------------------|
| 0.30| 0.1, 0.3, 0.7    |
| 0.50| ○, ○, ○, ○, ○    |

○: Cylindrical steel bar, □: Deformed steel bar

Fig. 22 Specimen configuration.

Fig. 23 Calculation procedure of corrosion quantity density.
6.3 Experimental result

Figure 24 shows the distribution of the corrosion quantity and corrosion weight loss. In this case, the water-cement ratio amounts to 0.50, crack width is 0.3 mm, and steel bar remains cylindrical. According to this figure, it can be confirmed that both distributions had the highest value at the segment located near a crack and were qualitatively the same.

Figure 25 shows the comparison of the corrosion weight loss converted from the corrosion quantity density and the corrosion weight loss obtained from the weight difference in all experimental cases. That is, the former is the value calculated in equation (20). According to this figure, it can be confirmed that the results were almost plotted on the straight line of 1:1. Therefore, it can be judged that both were equal. That is, though some researchers had reported the slightly different values of K in Equation (19) (Andrade 1978; Ohtsuka 1982; Yokota 1990), it is clarified that the actual amount of corrosion could be predicted when the value of (Tsuru 1979) under the AC impedance method shown in Fig.8. Furthermore, the corrosion current measured using a segmented steel bar evaluates the corrosion phenomenon of the rebar in concrete based on the following equation:

\[ CWL = \frac{CEQD}{F} \times 2 \times AW \]  

(26)

where CWL is the corrosion weight loss converted from the corrosion quantity density, CEQD is the corrosion quantity density (C/cm²), F is Faraday’s constant (96500 C), AW is the atomic weight of iron (55.85 g/mol), and 2 is the number of electrons generated by the anodic reaction of iron.

7. Conclusion

The conclusions are as follows, in the experimental conditions such as the water-cement ratio of the mortar was 0.30 and 0.50 with a normal Portland cement, and the steel bar with a diameter of about 10 mm with unit lengths of the segments of 5-65 mm.

1) This study established a method for measuring the...
corrosion current of steel while distinguishing macrocell from microcell currents, under specifically dividing the rebar embedded in a concrete specimen, whereby the macrocell current were defined as the current flowing between the segments, while the microcell current flowed in a segment.

2) The segment length did not influence the magnitude of the total corrosion current, which was the sum of both the macrocell anodic current and microcell current. Therefore, the total corrosion current density was equal to the steel corrosion rate at an actual concrete structure.

3) The magnitude of the macrocell current increases as the segment length decreased, while it decreased as the segment length increased. Therefore, it was necessary to use a segmented steel bar with a length of 15 mm or less to identify the location of the macrocell anode and measure the correct values of the macrocell anodic current.

4) The macrocell current between each segment could be measured by installing zero-resistance ammeter between neighboring segments.

5) The value converted from the corrosion current using electrical measurement methods became equal to the corrosion weight loss.

**Acknowledgement**

This paper is an extended English version of the previous work [Miyazato, S. et al., (2001). “The Experimental and Theoretical Investigation of Macrocell Current Measurement Method using Special Divided Steel Bar.” Proceedings of the Japan Concrete Institute, 23(2), 547-552. (in Japanese)]. This study was also supported by a Grant-in-Aid for Scientific Research (B) No. 20H0222400.

**References**

Andrade, C. and Gonzalez, J. A., (1978). “Quantitative measurements of corrosion rate of reinforcing steels embedded in concrete using polarization resistance measurements.” *Materials and Corrosion*, 29(8), 515-519.

Andrade, C., (2019). “Propagation of reinforcement corrosion: principles, testing and modelling.” *Materials and Structures*, 52, 2. Available at: <https://doi.org/10.1617/s11527-018-1301-1>.

Chen, E., Berrocal, C. G., Löfgren, I. and Lundgren, K., (2020). “Correlation between concrete cracks and corrosion characteristics of steel reinforcement in pre-cracked plain and fibre-reinforced concrete beams.” *Materials and Structures*, 53, 33. Available at: <https://doi.org/10.1617/s11527-020-01466-z>.

Choe, H., Nishio, Y. and Kanematsu, M., (2019). “A study on anti corrosion behavior of galvanized steel rebar in concrete under general and galvanic coupled environment.” *Journal of Structural and Construction Engineering*, 84(766), 1503-1512. (in Japanese)

Gu, X., Dong, Z. and Jin, Z., (2018). “Macrocell corrosion between crossed steel rebars embedded in concrete under chloride environments.” *MATEC Web of Conferences*, 199, 04005. Available at: <https://doi.org/10.1051/mateconf/201819904005>.

Hussain, R. R., (2011). “Electrochemical experimental measurement of macrocell corrosion half-cell potential replicating the re-corrosion of actual refurbished works in RC structures.” *International Journal of Electrochemical Science*, 6(1), 199-205.

Itagaki, M., (2012). “Principle and analytical method of impedance spectroscopy.” *Journal of the Surface Science Society of Japan*, 33(2), 64-68. (in Japanese)

Katayama H., (2014). “Surface and interfacial analysis using electrochemical impedance measurement.” *Journal of Japan Institute of Metals and Materials*, 78(11), 419-425. (in Japanese)

Kawahigashi, T., Kobayashi, K. and Miyagawa, T., (2003). “A study of macro-cell and micro-cell corrosion of steel in concrete.” *Translation from Proceedings of JSCE*, 59(732), 65-82.

Kobayashi, K. and Miyagawa, T., (2001). “Study on estimation of corrosion rate of reinforcing steel in concrete by measuring polarization resistance” *Journal of JSCE*, 50(669), 173-186. (in Japanese)

Maruya, T., Takeda, H., Horiguchi, K., Koyama, S. and Hsu, K.-L., (2007). “Simulation of steel corrosion in concrete based on the model of macro-cell corrosion circuit.” *Journal of Advanced Concrete Technology*, 5(3), 343-362.

Miyazato, S. and Otsuki, N., (2010). “Steel corrosion induced by chloride or carbonation in mortar with bending cracks or joints.” *Journal of Advanced Concrete Technology*, 8(2), 135-144.

Miyazato, S. and Hanaoka, D., (2020). “Macrocell corrosion and its countermeasure for reinforced concrete after patch repair.” *Advanced Materials Letters*, 11(6), 20061528.

Mohammed, T. U., Otsuki, N. and Hamada, H., (2001a). “Oxygen permeability in cracked concrete reinforced with plain and deformed bars.” *Cement and Concrete Research*, 31(5), 829-834.

Mohammed, T. U., Otsuki, N., Hisada, M. and Shibata, T., (2001b). “Effect of crack width and bar types on corrosion of steel in concrete.” *Journal of Materials in Civil Engineering*, 13(3), 194-201.

Mohammed, T. U., Otsuki, N., Hamada, H. and Yamaji, T., (2002). “Chloride-induced corrosion of steel bars in concrete with presence of gap at steel-concrete interface.” *ACI Materials Journal*, 99(2), 149-156.

Mohammed, T. U., Hamada, H., Ariful, H. and Mohammed, A. A. M., (2015). “Corrosion of steel bars in concrete with the variation of microstructure of steel-concrete interface.” *Journal of Advanced Concrete Technology*, 13(4), 230-240.
Nanayakkara, O. and Kato, Y., (2009). “Macro-cell corrosion in reinforcement of concrete under non-homogeneous chloride environment.” *Journal of Advanced Concrete Technology*, 7(1), 31-40.

Nishida, T., Otsuki, N. and Konagai, A., (2003). “Corrosion rate of steel bar at joint and its control method in reinforced concrete members induced by carbonation.” *Journal of the Society of Materials Science*, 52(9), 1067-1074. (in Japanese)

Ohtsuka, T. and Sato, N., (1982). “Measurements of the corrosion rate of iron in aqueous solution by means of a square wave current polarization with compensation of solution resistance.” *Corrosion Engineering*, 31(5), 336-342. (in Japanese)

Otsuki, N., Madlangbayan, M. S., Nishida, T., Saito, T. and Baccay, M. A., (2009). “Temperature dependency of chloride induced corrosion in concrete.” *Journal of Advanced Concrete Technology*, 7(1), 41-50.

Otsuki, N., Miyazato, S., Diola, N. B. and Suzuki, H., (2000). “Influences of bending crack and water-cement ratio on chloride-induced corrosion of main reinforcing bars and stirrups.” *ACI Materials Journal*, 97(4), 454-464.

Paul, S. C. and Babafemi, A. J., (2018). “A review on reinforcement corrosion mechanism and measurement methods in concrete.” *Civil Engineering Research Journal*, 5(3), 80-90.

Paul, S. C. and van Zijl, G. P., (2014). “Crack formation and chloride induced corrosion in reinforced strain hardening cement-based composite (R/SHCC).” *Journal of Advanced Concrete Technology*, 12(9), 340-351.

Qiao, D., Nakamura, H., Yamamoto, Y. and Miura, T., (2016). “Modeling of corrosion-induced damage in reinforced concrete considering electro-mechanical coupling.” *Journal of Advanced Concrete Technology*, 14(11), 664-678.

Raupach, M. and Büttner T., (2014), “Concrete repair to EN 1504.” CRC Press, 29-30.

Sandra, N., Kawaai, K. and Ujike, I., (2019). “Corrosion current density of macrocell of horizontal steel bars in reinforced concrete column specimen.” *International Journal of GEOMATE*, 16(54), 123-128.

Schiessl, P., Breit, W. and Raupach, M., (1994). “Durability of local repair measures on concrete structures damaged by reinforcement corrosion.” *SP145: Proceedings of Third CANMET - ACI International Conference for Durability of Concrete*, 1195-1216.