

# ANALYTICAL METHODS TO EVALUATE MACRO-CELL CORROSION CURRENTS IN CONCRETE

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## ABSTRACT

Electrochemical parameters, i.e. half-cell potentials, concrete resistances and polarization resistances were measured in a concrete specimen with a segmented steel bar which can also measure the direct macro-cell currents. Measured parameters were used to calculate and compare the macro-cell current along a segmented steel bar. It has been found that the results from those analytical methods (1 & 2) do not compatible with the practically measured macro-cell currents (method 3). However, the method 1 which uses the effect of polarization resistance gives more appropriate macro-cell currents. **Keywords:** macro-cell corrosion, corrosion currents, electrochemical parameters

## 1. INTRODUCTION

Reinforcing steel in concrete is naturally protected by the passive oxide film. However, the penetration of chloride ion into concrete destroys the passive film and hence the corrosion starts. Chloride ion mainly generates macro-cell type corrosion in concrete.

Macro-cell corrosion is the spatial separation of anodic and cathodic reactions along the steel bar. Based on the spatial separation, it generates local anode with a comparatively large cathode to produce local rust. However, due to its nature macro-cell behaviour cannot be clearly identified by the available non-destructive testing including half-cell measurements. Hence the importance of macro-cell corrosion is emphasized.

To clarify the characteristics of macro-cell corrosion, an experimental setup with a segmented steel bar [1] has been introduced. As this technique is valid only in experimental situation, theoretical calculation methods are important to identify the magnitude and the behavior of macro-cell corrosion. Some researchers [1, 2] have developed methods to calculate the amount of macro-cell current. For these calculations, basic electrochemical parameters of corrosion are used. The parameters used for the calculation depend on the particular method. Although there are methods, the applicability and the accuracy of these methods and their comparisons are rarely performed.

In this study, the main objective is to calculate the macro-cell currents using abovementioned techniques and to compare the macro-cell current variation among those methods. For the calculations, half-cell potential, concrete resistance and the polarization resistance along the steel bar was used. The variation of macro-cell corrosion in different environment was also discussed.

## 2. METHODS FOR THE ESTIMATION OF MACRO-CELL CORROSION CURRENTS

### 2.1 Electrical circuit method (Method 1)

Measured half-cell potentials, concrete resistances and polarization resistances at a regular interval along the re-bar are used to calculate the macro-cell current produced or consumed for a given location. The method is briefly explained in this paper (as in the Fig. 1) and it is explained in detail by the Miyazato [1]. Ohms law (Eq. 1) and Kirchoff's law (Eq. 2) are used to calculated macro-cell current ( $I_1, I_2$  etc.) for each location. Based on the measured interval and the sensor used to measure polarization resistance, the surface area of the imaginary element is decided. Hence, the macro-cell current density can be calculated.

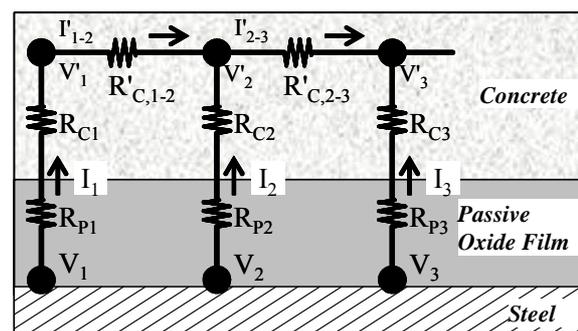


Fig.1 Electrical circuit method to calculate macro-cell currents

$$\frac{V'_1 - V_1}{R_{P1} + R_{C1}} = I_1; \frac{V'_2 - V'_1}{R'_{C,1-2}} = I'_{1-2}; \frac{V'_2 - V_2}{R_{P2} + R_{C2}} = I_2; \dots (1)$$

$$I_1 - I'_{1-2} = 0; I'_{1-2} + I_2 - I'_{2-3} = 0; \dots (2)$$

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$V_1, R_{C1}, R_{P1}$  - Measured half-cell potential (-mV), concrete resistance (k $\Omega$ ), polarization resistance (k $\Omega$ ) respectively at location 1.

$R'_{C,1-2}$  - Average concrete resistance (k $\Omega$ ) between location 1 and 2.

$V'_1, V'_2, V'_3 \dots$  - Arbitrary potentials (-mV) used for calculations.

$I'_{1-2}, I'_{2-3} \dots$  - Arbitrary currents ( $\mu$ A) used for calculations.

$I_1$  - Macro-cell current ( $\mu$ A) at location 1.

Negative macro-cell currents represent anodic locations.

## 2.2 Multi circuit method (Method 2)

Measured half-cell potentials and concrete resistances at a regular interval along the re-bar are used to calculate the macro-cell current. Considering the arbitrary elements of the re-bar, macro-cell current at a target element  $j$  can be calculated [2] taking the effect of all other remaining  $k$  elements. The method is illustrated by the Fig. 2 and the calculation method is explained by the Eq. 3 and Eq. 4.

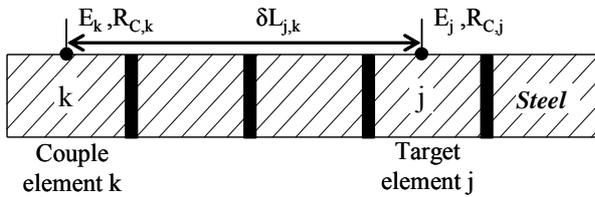


Fig.2 Multi circuit method to calculate macro-cell currents

$$\delta E_{j,k} = E_k - E_j = \delta L_{j,k} \cdot w \cdot I_{j,k} \quad (3)$$

$$I_j = \frac{1}{B \cdot \Delta L_j} \sum_{k=1}^n \frac{\delta E_{j,k}}{w \cdot \delta L_{j,k}} \cdot B \cdot \Delta L_k \quad (4)$$

$E_j, E_k$  - Half-cell potentials (-mV) at element  $j$  and  $k$  respectively.

$R_{C,j}, R_{C,k}$  - Concrete resistances (k $\Omega$ ) at element  $j$  and  $k$  respectively.

$w$  - Specific concrete resistivity (k $\Omega$ cm)

$\delta L_{j,k}$  - Distance (cm) between element  $j$  and  $k$ .

$B$  - Width of element (cm).

$\Delta L_j, \Delta L_k$  - Lengths of element  $j$  and  $k$  respectively.

$n$  - Number of elements.

$I_{j,k}$  - Macro-cell current ( $\mu$ A/cm<sup>2</sup>) of target element  $j$  by couple element  $k$ .

$I_j$  - Macro-cell current ( $\mu$ A/cm<sup>2</sup>) of target element by all elements.

## 2.3 Segmented steel bar method (Method 3)

A segmented steel bar is used to measure the macro-cell current passing through the connectors in between elements [1] as shown in the Fig. 3. These currents are used to evaluate the current consumed or produced by each element. Individual current is further converted to the current density (Eq. 5). Elements are being connected at their exposure period, however, they are temporarily disconnected to measure the currents.

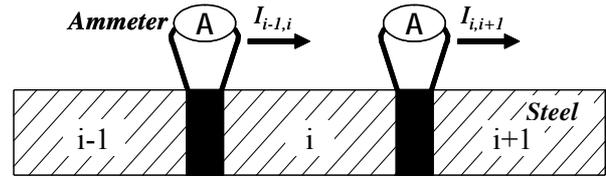


Fig.3 Experimental measurement method of macro-cell corrosion current

$$a_i = \frac{I_{i,i+1} - I_{i-1,i}}{S_i} \quad (5)$$

$I_{i,i+1}, I_{i-1,i}$  - Corrosion currents ( $\mu$ A) passing through element  $i$  to  $i+1$  and  $i-1$  to  $i$  respectively,

$S_i$  - Surface area (cm<sup>2</sup>) of element  $i$ .

$a_i$  - Macro-cell current density.

## 3. TEST PROGRAM

### 3.1 Materials

#### (1) Concrete

Ordinary Portland Cement (OPC) was used for the concrete mix of W/C 0.55. The mix proportion of the concrete is given in the Table 1. Maximum size of 13 mm coarse aggregate was used keeping s/a as 45%. Unit weight of fine aggregate (S) and coarse aggregate (G) are 2.63 g/cm<sup>3</sup> and 2.70 g/cm<sup>3</sup> respectively. For the locations where chloride added concrete is needed, an amount of chloride ions of 19.2 kg/m<sup>3</sup> by the mass of concrete is added to the concrete during mixing.

Table 1 Mix proportion of concrete

Unit weight of materials (kg/m <sup>3</sup> )				AE (%×C)
W	C	S	G	
190	345	770	966	0.002

#### (2) Segmented steel bar

A 16 mm diameter of plain steel bar was used to make the segmented bar. It consists of 20 equal steel elements where the length of one element is 50 mm. A gap of 50 mm between elements was created and filled by acrylic for the purpose of measuring the polarization resistance without the effect of adjacent elements. Each element was connected to the adjacent elements (refer the Fig. 4) using lead wires so that the macro-cell currents are flowing only through the wires.

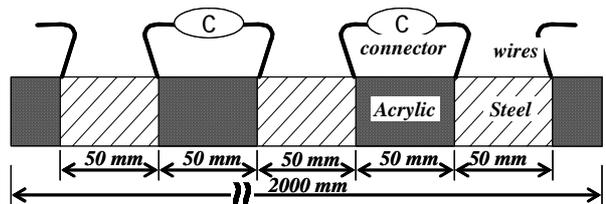


Fig.4 View of the segmented steel bar

### 3.2 Preparation of Specimens

The size of concrete specimen was 100x100x2000 mm<sup>3</sup>. Specimen has different concrete sections, first with an amount of 19.2 kg/m<sup>3</sup> chloride ions having a length of 400 mm in either side from the

center of the specimen. Second, remaining all area consists of concrete having the no chloride ions (refer the Fig. 5). This method was deliberately adopted to increase the activity of macro-cell corrosion. Segmented steel bar was placed having a cover thickness of 20 mm from the bottom of the specimen. The specimen was sealed and cured for 7 days from the casting and then its all surfaces were epoxy coated except the cover concrete so that the oxygen and moisture transportation occurs only through the cover concrete.

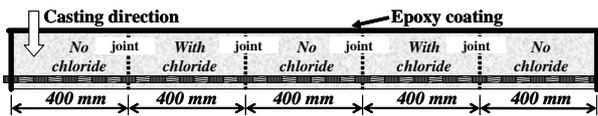


Fig.5 View of the concrete specimen

After the epoxy coating, the specimen was subject to an exposure condition of relative humidity of 60 % and the temperature of 20 °C continuously. Specimen was subject to a wetting period of 12 hour once in every week where the measurement was taken at the end of the wetting period. Analysis and discussion in this paper based on the measurement data at the 6<sup>th</sup> measurement, i.e. at the 42 days of exposure from the epoxy coating. Measurements of half-cell potentials, concrete resistance and the polarization resistance were taken for every elements and the sensor of the corrosion meter was placed exactly above the center of a particular element. Measurements of macro-cell currents flowing between elements were also taken simultaneously by a macro-cell adaptor.

#### 4. EXPERIMENTAL RESULTS

##### 4.1 Half-cell potential variation

Fig. 6 shows the variation of half-cell potential along the segmented steel bar. Compared to the no chloride region, more negative half-cell potential data can be observed in the region of having chloride ion. This fact is obviously due to the corrosion activity of that particular region. However, the potential of 90 % corrosion probability for the electrode used to measure the half-cell potential in the specimen is exceeded by the all measured potentials regardless whether the measurement locations are in region with chloride or without chloride. This particular behaviour occurs mainly due to the generation of macro-cell corrosion where macro-cell anodic reaction is activated in the region with chloride while the remaining area is affected by the macro-cell cathodic reaction. Therefore, the calculated macro-cell currents are a suitable parameter to discuss and investigate the behavior of macro-cell corrosion process.

##### 4.2 Polarization resistance and concrete resistance

Measured polarization and the concrete resistance of the elements of the segmented steel bar are plotted as in the Fig. 7. It can be understood that the polarization resistance which is generated by the

availability of the passive oxide film due to the ongoing corrosion process of the steel bar is comparatively much higher than the concrete resistance. Though it is not valid for the middle section with no chloride of the specimen, the polarization resistance values are higher in no chloride regions. It is indirectly confirmed their low activity of corrosion at the region of no chloride. The deviation of concrete resistance is not high compared to the polarization resistance; however there is a considerable amount of difference in with and no chloride regions. The average measured concrete resistance at the region of with chloride is 0.48 kΩ and it is 1.20 kΩ at the region of no chlorides. This result confirms the fact that chloride ion themselves causes to vary the resistance of concrete although the moisture condition kept uniform throughout the specimen.

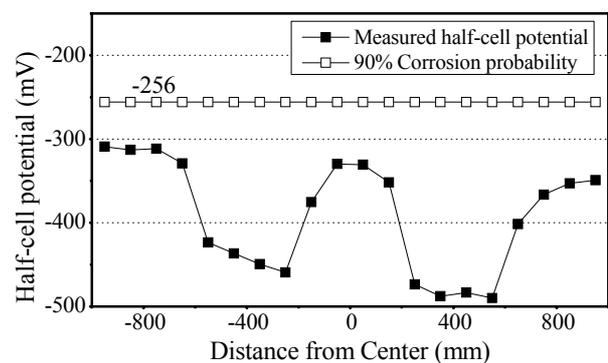


Fig.6 Half-cell potential variation

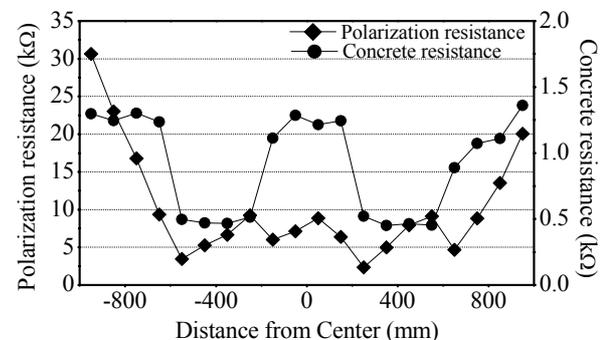


Fig.7 Polarization and Concrete Resistance

##### 4.3 Macro-cell current calculated by Method 1

Measured half-cell potential, concrete resistance and the polarization resistance were combined together using the method 1 explained in section 2.1 to calculate the macro-cell current at every element and is plotted in the Fig. 8. Negative currents represent the locations of anodic reaction. Though the half-cell measurements shows only the potential, the method of electric circuit combining all electrochemical parameters to calculate the current gives a proper variation of macro-cell behavior. The results show that the macro-cell anodic currents are generated at the region with chloride ions and macro-cell cathodic currents are generated at the regions of having no chlorides in this specimen. Not a single element, but all elements in chloride region show macro-cell anodic behaviour by this method.

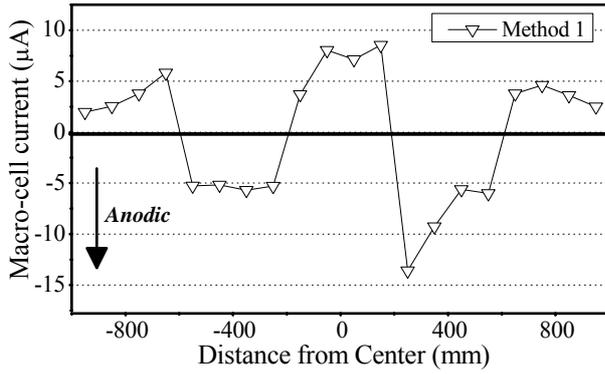


Fig.8 Macro-cell current by Method 1

#### 4.4 Macro-cell current calculated by Method 2

Measured half-cell and concrete resistance are used to calculate the macro-cell current using the method 2. It is noted here that this method does not need to consider the polarization resistance values of elements.

In this method, macro-cell currents are calculated considering different possibilities of the value of specific resistivity of concrete. In the case of wet concrete, a constant value of 1.8 kΩcm is recommended in previous research [3]. Hence a constant value is used for the calculation and resulted macro-cell current variation is represented in the Fig. 9. However, as explained in the section 4.1 related to Fig. 4, the concrete resistance is not uniform along the steel bar especially when the concrete is subject to chloride penetration. In this particular situation, it is not acceptable to use a constant value for the specific resistivity of concrete. Hence, in the calculations, the measured concrete resistance was converted to the specific resistivity ( $w$ ) for all elements individually using the Eq. 6. When the currents are calculated in between the target element and the couple element, the average specific resistivity ( $w_{ave}$ ) was used as the specific resistivity differs along the steel bar. Therefore, it can be argued that the macro-cell currents by using the value of  $w_{ave}$  are more appropriate than the consideration of constant  $w$ .

$$R_c = w \frac{L}{A} \quad (6)$$

$R_c$  - Measured concrete resistance at a given location.  
 $w$  - Calculated specific resistivity of concrete.  
 $A$  - Area covered by the particular element ( $cm^2$ ).  
 $L$  - Distance from the concrete surface to the steel element surface (cm).

Calculated macro-cell currents taking  $w_{ave}$  is represented in Fig. 9. It can be observed that in this situation the difference of macro-cell currents are not significantly high and also the trend of curves are not affected though a constant specific resistivity is used. As the measured concrete resistances are comparatively low, the macro-cell currents calculated using measured values are slightly higher than the values calculated having a constant specific resistivity.

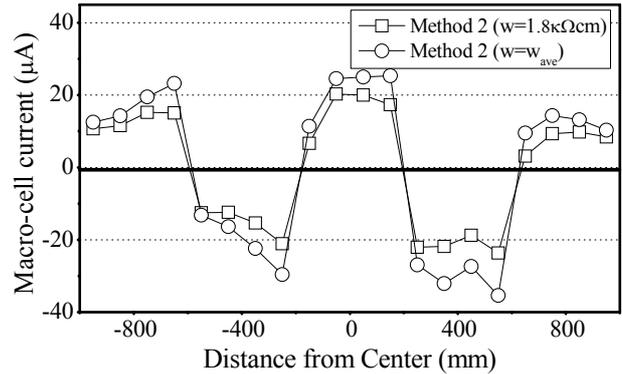


Fig.9 Macro-cell current by Method 2

#### 4.5 Effect of wet and dry regions on macro-cell current calculated by Method 2

In this particular test, concrete specimens were kept wet for 12 hours before obtaining its electrochemical parameters. Therefore regardless of the chloride content in specimens, the moisture content is assumed to be uniform over the steel bar. However, concrete resistance is not uniform because of the available chloride ions as explained in the section 4.2.

Above explanation can be used to evaluate a practical aspect of the combined variation of both chloride ions and the moisture condition along the steel bar. In real situation, when the chloride ion penetrates to concrete section, that particular area is subject to wet condition in the form of either submerging or water spraying. Hence for this calculation, it is assumed that the wet condition is prevailed in the region of having chloride ions and no chloride region is under dry condition. For this purpose, results of this test, i.e. the average concrete resistance of 0.48 kΩ was used for individual elements in the chloride entered region. For the no chloride region the average concrete resistance of 1.20 kΩ was increased by a factor of 2.78 where the factor is decided by the ratio between dry and wet concrete resistivity. In the case of dry concrete, a constant value of 5.0 kΩcm is recommended in previous research [3]. The measured half-cell potentials were directly used. Though the current variation is theoretically acceptable, in this study it was not experimentally proved how the currents are varied when different moisture conditions are considered.

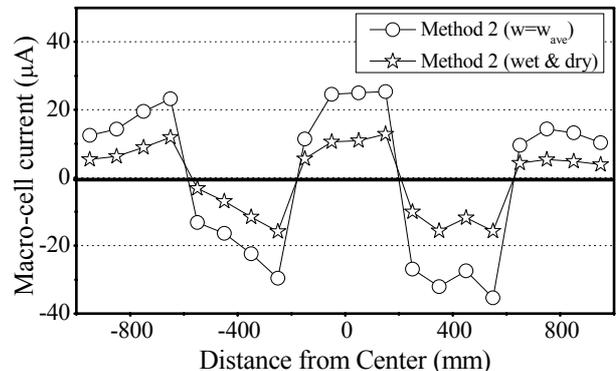


Fig.10 Macro-cell current by Method 2 (effect of wet and dry regions)

According to the calculated values of macro-cell current as shown in the Fig. 10, it can be clearly identify that macro-cell currents are decreased when the concrete resistivity is increased or on the other hand when the condition of concrete is dry in the region of no chloride. This result depends on the theoretical background of the method used to calculate the macro-cell current. Macro-cell corrosion is generated when a clear spatial separation is formed in between anodic and cathodic regions. Once the separation is formed, the resistivity of electrolyte, i.e. the concrete media plays a major role to generate macro-cells current.

#### 4.6 Comparison of macro-cell current by Method 1 and Method 2 considering the effect of $R_p$

In the case of method 1, the measured polarization resistance was taken into account when the calculation is carried out because method 1 explains how the polarization resistance is used. However, the method 1 can still be used to evaluate the macro-cell currents when the polarization resistance was not taken into account. It means the polarization resistance equalize to zero ( $R_p=0$ ).

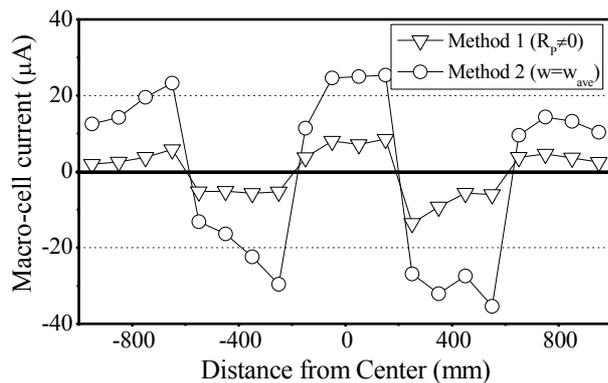


Fig.11 Macro-cell current comparison ( $R_p \neq 0$ )

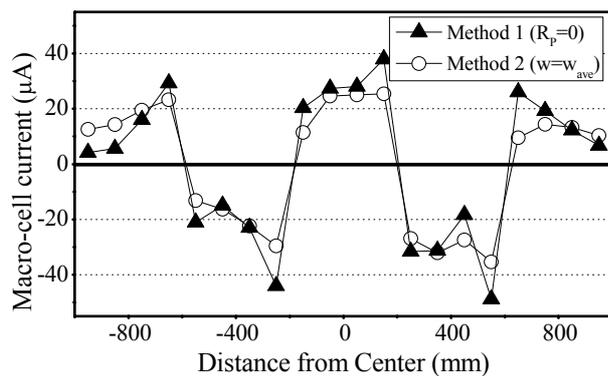


Fig.12 Macro-cell current comparison ( $R_p = 0$ )

Fig. 11 shows the macro-cell corrosion currents calculated by method 1 and 2 which were also demonstrated in the Fig 8 and Fig. 9. Based on the direct comparison, the difference of macro-cell currents calculated by method 1 and 2 is significantly high. This is due to the increased resistance of macro-cell circuit. On the other hand, once the polarization resistance is not taken into account for the calculation in method 1,

the macro-cell currents are similar for both methods as shown in the Fig.12. This result can prove that the polarization resistance can vary the calculated macro-cell currents significantly. Also it proves that the currents are matching and hence both methods are applicable to calculate macro-cell currents only when the half-cell potential and the concrete resistance are taken into account. However, it is well known that when the corrosion starts the passive oxide layer is destroyed towards the low polarization resistance and it is comparatively high if the corrosion has not yet started.

#### 4.7 Macro-cell current by Method 3

The third method is purely an experimental method to investigate the variation of macro-cell currents. Directly measured macro-cell currents which flows in between elements are converted to macro-cell current produced or consumed by individual elements (refer to Fig. 13).

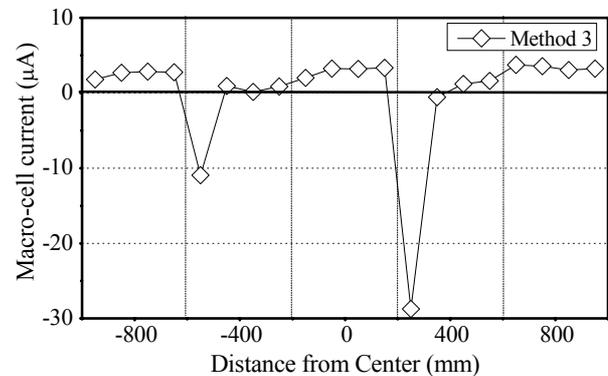


Fig.13 Macro-cell current by Method 3

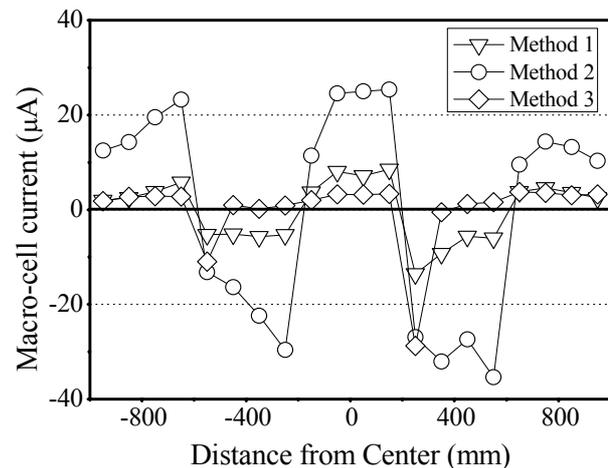


Fig.14 Macro-cell current comparison by Method 1, 2 and 3

It can be observed here that the practically measured anodic macro-cell currents are more local than the anodic macro-cell current calculated by method 1 and 2 referring to the Fig. 13 and Fig. 14. Further explaining, anodic macro-cell currents are generated in all elements in the region with chloride ions in the case of method 1 and 2. However, in the

case of method 3, just an element of each chloride region shows macro-cell corrosion behavior. Strictly, both method 1 and 2 are not compatible with the practically measured macro-cell currents making a doubt for the author regarding the accuracy of any of these methods. However, just observing the trend of currents, significance of the difference of results between the method 1 and 3 is low compared to results between 2 and 3.

#### 4.8 Total corrosion current

To investigate further, total corrosion current of the elements of the segmented steel bar was calculated based on the Eq.7 and is plotted in the Fig.15. It is noted here that total current represents both macro-cell and micro-cell currents. Also, noted that there are no positive (cathodic) currents in this method.

$$I = \frac{K}{R_p} \quad (7)$$

I - Total corrosion current ( $\mu\text{A}$ )

K - Constant (26 mV)

$R_p$  - Polarization resistance (k $\Omega$ )

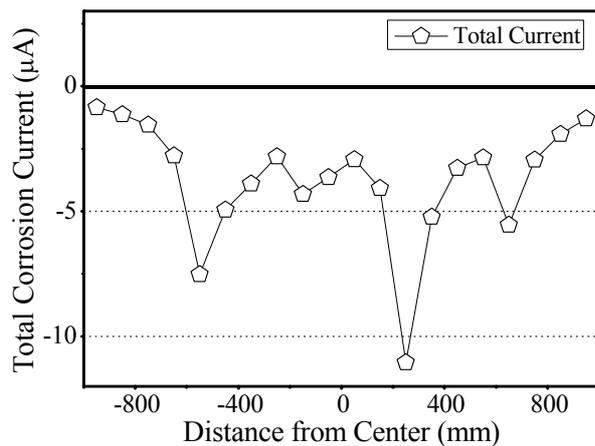


Fig.15 Total corrosion current

Comparing the Fig. 15 and Fig. 13 the elements with the highest macro-cell corrosion currents are matching. However, their magnitudes are significantly differing from each other and more importantly, at these locations; the total corrosion currents are smaller than the practically measured macro-cell corrosion currents. This is either be a practical error occurred when the measurements were taken or be a wrong implementation of the macro-cell current data which brings the need of more clarifications related to macro-cell corrosion in concrete.

#### 5. CONCLUSIONS

In this research study, basic three electrochemical parameters i. e. half-cell potential, concrete resistance, polarization resistance needed for the evaluation of corrosion situation in concrete were measured for a specimen with a segmented steel bar.

1. It was observed that a significant variation of

polarization resistance in between with chloride and no chloride region of concrete. Concrete resistance also varies against the chloride content in concrete.

2. A clear variation of half-cell potential is observed between with and without chloride regions. However, the measured half-cell potentials at all locations exceed the recommended the level of 90 % corrosion probability which is affected by the macro-cell reaction.

3. The calculated macro-cell currents by using the method 1 and 2 are not matching when the polarization resistance is taken into account for the method 1. However, calculated results are nearly identical once the polarization resistance is neglected from the calculation setup.

4. None of the method 1 and 2 are compatible with the practically measured macro-cell current (method 3) using the advantage of the segmented steel bar. However, the error between method 1 and 3 is less significant as the polarization resistance is taken into account.

5. Only the locations of highly active macro-cells can be captured even from the total corrosion current variation, however their magnitude makes the necessity of more theoretical and experimental background related to macro-cell corrosion.

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