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# Corrosion rate measurement of multiple reinforcements using the galvanostatic pulse technique with the guard ring

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**Abstract:** This study investigates the corrosion rate measurements for multiple reinforcements in concrete by using the galvanostatic pulse technique. In order to know whether or not this technique can distinguish corrosion status for multiple reinforcements covered by the guard ring, two programs were conducted. For the first stage, a reinforcement was embedded in two concrete blocks and the part of reinforcement in one of the block was in a corrosion environment while another part of reinforcement in another block was not in a corrosion environment. Results reconfirmed that the galvanostatic pulse technique detected the local corrosion current owing to the help from guard ring. For the second stage, two parallel reinforcements (one epoxy-coated reinforcement and one plain reinforcement) were embedded in a chloride contaminated concrete block. Results showed that when two reinforcements were covered by guard ring, the galvanostatic pulse technique could not distinguish the corrosion current for each individual reinforcement and an average value would be obtained. In such a case, for the reinforcement which was not corroded one may overestimate its corrosion rate, and for the reinforcement which was corroded one may underestimate its corrosion. Therefore, results imply that a C-scan method (which is commonly used for the ultrasonic testing) may be required to obtain a correct measurement of corrosion rate.

**Key words:** corrosion rate, galvanostatic pulse technique, guard ring, C-scan

## 1. INTRODUCTION

Corrosion of reinforcements is one of the major deterioration for reinforced concrete structures. Therefore, to determine the instantaneous corrosion rate of reinforcement become an important issue. Several techniques have been developed to detect the instantaneous corrosion rate of reinforcement, e.g., the DC (Direct Current) linear polarization, AC (Alternating Current) impedance method and galvanostatic pulse method [1,2]. With the aid of the guard ring, these techniques can detect the local corrosion status of reinforcements.

Wojtas [3] studied the error of sensorized guard ring and concluded that when the reinforcement is passive the corrosion rate is overestimated, and when the corrosion is localized, the corrosion rate of the corroding part is seriously underestimated even for a relatively large size of the active spot. Andrade and Alonso [4] studied the factors influencing the corrosion rate measurement using guard ring including the values of the time of wetness, as well as of the climatic parameters which influence the moisture content of the concrete. Song [5] discussed the three theoretical problems in the application of the polarization resistance technique with the guard ring. Elsener [6] investigated the influence of the conductivity and cover depth on potential and macrocell current distribution have been studied both in open circuit conditions and under external anodic polarization. Since most of the DC current applied by an external counter electrode on the concrete surface placed over the active/passive macrocell flows to the local anode despite the large cathode area (anode/cathode area ratio 1:60), Elsener [6] concluded that polarization resistance measurements on locally corroding reinforcements would result in an erroneous corrosion rate of the anode, the error could arise to a factor of 10. Andrade and Martìnez [7] investigated the calibration of corrosion rate measurements with the modulated confinement of the current method (MCC), comparing the electrochemical results with the gravimetric losses of the reinforcements. Wojtas [8] reported that modulated guard ring electrode arrangement failed to confine the lateral spread of the counter electrode current within a constant area. Using the constant diameter of confinement for the calculation of corrosion rate might lead to serious errors when test conditions change. When high corrosion activity of reinforcement and/or local corrosion occurred, the use of the modulated GE confinement might lead to significant underestimation of the corrosion rate. Elsener [9] discussed corrosion rate measurements of steel in corrosion and gave some important points beyond the Tafel law. Law et al. [10] investigated the effect of electrode orientation on linear polarization measurements using the sensor controlled guard ring. The sensor orientation was not observed to affect the polarization resistance measurements taken on actively corroding steel next to passive steel. Feliu et al. [11] investigated the possibilities and problems of in situ techniques for measuring steel corrosion rate in large reinforced concrete structures. Two problems were concerned: (i) the time constant value associated with the corrosion process, and (ii) the use of a guard ring for confining the electrical signal to a definite reinforcement area. In (i), their results corroborated the assumption of a time constant value independent of the area affect by the electrical signal, albeit with some exceptions. In (ii), the results showed the great importance of achieving a critical ratio between the current intensities that flowed from the guard ring and counter-electrode. Poursaee and Hansson [12] compared the measurements from the galvanostatic pulse technique with the current confinement guard ring with the finite element analysis.

In this paper, the effects of multiple reinforcements on the corrosion rate measurements by the galvanostatic pulse technique with the sensor controlled guard ring were investigated. Considering the scenario that two reinforcements are electrically connected and one of them is corroded while another is not. When the galvanostatic pulse measurement is performed, these two reinforcements are all covered by the guard ring. What signal will we obtain then? In laboratory, a single reinforcement was used to simplify the investigation and it is commonly seen in most research papers. However, in the real world there exist multiple reinforcements inside the reinforced concrete structure. These reinforcements are electrically connected together, e.g., the steel reinforcement cage. Then, can the galvanostatic pulse technique with the sensor controlled guard ring detect the local corrosion of one of the reinforcement is an important issue. We will answer this question in this article through the experimental study stated in the follows.

## 2. EXPERIMENTS

### 2.1 Two experiment programs

Two experiments programs were conducted. In the first program, the local detection capability of the galvanostatic pulse technique with the sensor controlled guard ring was confirmed. In the second program, the factor of multiple reinforcements was then investigated.

In the first program, a single #4 reinforcement was embedded in two concrete blocks as shown in Fig. 1(a). The reinforcement was first immersed in a 3.5% NaCl solution for 1 week, then it was taken out and corrosion rust on some part of the reinforcement was cleaned to fresh metallic surface. After the above treatment, one can easily tell that the part without cleaning rust was still active while the part with cleaning process recovered to the passive state. The active part was embedded in one of the concrete block and the passive part was embedded in another concrete block. In addition, two kinds of concrete blocks were prepared. The first group used concrete without adding any NaCl and another group used 5% NaCl addition (by the cement weight) to simulate the seriously contaminated environment. No matter which condition is applied, it is expected that the galvanostatic pulse technique with the sensor controlled guard ring can distinguish the corrosion statuses for the active part and passive part, although they are all in one reinforcement. Two water/cement (w/c) ratios for concrete mixtures (0.4 and 0.6) were used to investigate the influence of water/cement ratio.

In the second program, the factor of multiple reinforcements was considered. Two parallel #4 reinforcements were embedded in one concrete block as shown in Fig. 1(b). These two reinforcements were electrically connected by a steel wire. One reinforcement was first immersed in 3.5% NaCl solution for 1 week to generate rust while the other was coated with epoxy with the thickness of epoxy is 150 μm to protect the steel from chloride attack. A 5% NaCl addition (by cement weight) was added to simulate a seriously contaminated environment. In this stage, only water/cement ratio of 0.4 was used. For both programs, all specimens were cast and then cured by steam curing for 1 day. The pre-steaming period was 3-h, and the rate of heating was 15 °C /h to reach the maximum temperature of 80 °C. The soaking time of the maximum temperature lasted 13h, then specimens were cooled at the cooling rate of 25 °C /h. Then, specimens were demoded and placed in the environment chamber (80% relative humidity, 25°C). Electrochemical measurements were conducted at designated ages. For specimens of the first program, only the 28-day values were reported. For specimens of the second program, values were measured for 1-day, 7-day, 14-day and 28-day. When the electrochemical measurements were made, the specimens were taken out from the environment chamber. Otherwise, the specimens were placed in the chamber to maintain the humidity and temperature unchanged.

For the second program, four kinds of instrument arrangements were designed. For the first kind arrangement, only corroded reinforcement was detected. For the second kind, only epoxy-coated reinforcement was detected. For the third and fourth kind, two reinforcements were both under the guard ring. For the third kind, the corroded reinforcement was near the sensor and the epoxy coated reinforcement was far away from the sensor. For the fourth kind, the epoxy coated reinforcement was near the sensor and the corroded reinforcement was far away from the sensor.

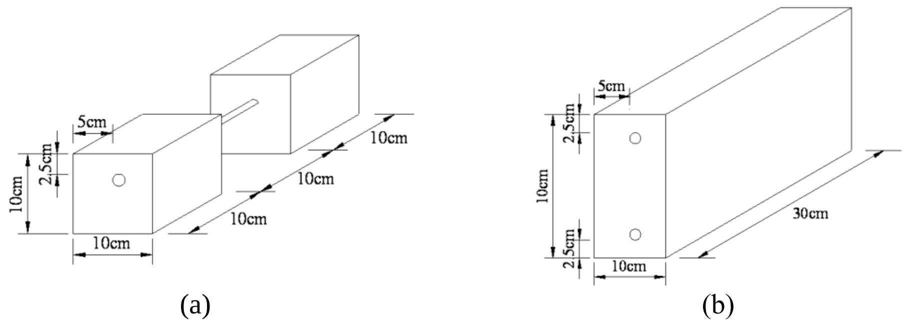


**Figure 1.** Specimen illustration: (a) the first program; (b) the second program.

### 3.2 Concrete mixtures and materials

Concrete mixtures with two water/cement ratios were used as shown in Table 1. The cement used was type I cement. The coarse aggregate had its saturated and surface dry specific weight of 2.67, water absorption of 1.5%, maximum size of 12.5 mm, oven-dry density of 1600 kg/m$^3$ and fineness modulus of 6.58. The fine aggregate had its saturated and surface dry specific weight of 2.51, water absorption of 4.8% and fineness modulus of 2.89. The #4 reinforcement was used. The NaCl powder with purity higher than 99.8% was adopted to add in the concrete to simulate the contaminated concrete. For the second program, only w/c=0.6 was adopted. For each configuration, five specimens were prepared.

**Table 1.** Concrete mixtures

| w/c ratio | Water (kg/m$^3$) | Cement (kg/m$^3$) | Fine aggregate (kg/m$^3$) | Coarse aggregate (kg/m$^3$) |
|---|---|---|---|---|
| 0.4 | 200 | 500 | 639 | 976 |
| 0.6 | 200 | 333 | 771 | 976 |

### 3.3 Galvanostatic pulse technique

The instantaneous corrosion rate was measured using the apparatus GPM-5000 manufactured by German Instruments. The GPM-5000 first measured the open circuit potential for the reinforcement. A pulse of current of this corrosion potential (usually 5 to 40 mA) was released for 10 seconds (suggested instrumental setup), the current was cut off. After cutoff, the measurement of potential could be carried out as shown in Fig.2. The value for potential can be expressed by the following formula [13]:

$$V_t=I_{app}[R_p[1-\exp(-t/R_pC_{dl})]+R_W] \quad (1)$$

where $V_t$ (vol) is the potential at time $t$, $I_{app}$ (μA/cm$^2$) is the difference between current densities, $R_p$ (Ohm-cm$^2$) is polarization resistance, $C_{dl}$ (Columb/mol) is the double layer capacitance and $R_W$(Ohm-cm$^2$) is the resistance from the surrounding environment. From eq.(1), one can obtain

$$\ln(V_{max}-V_t)=\ln(I_{app}R_p)-t/(R_pC_{dl}) \quad (2)$$

where $V_{max}$ is the steady-state potential.

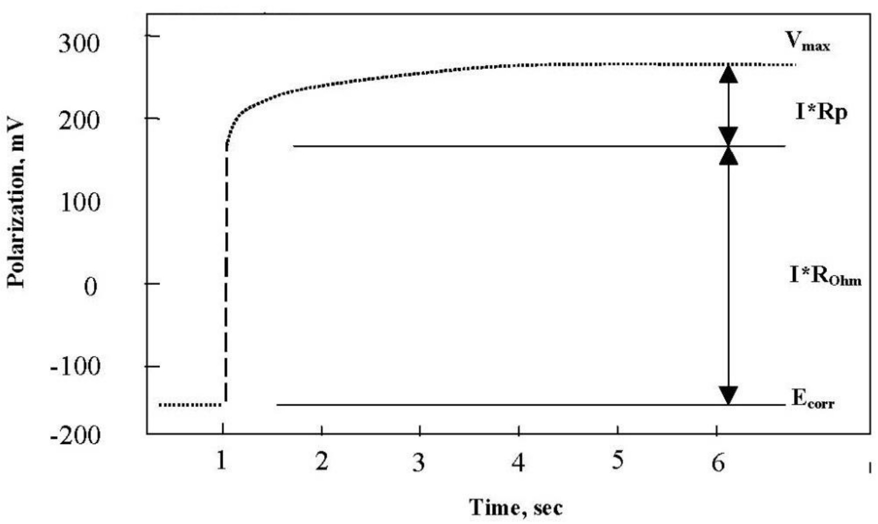


**Figure 2.** A typical diagram for andic polarization after the cutoff of current for GPM.

Using the diagram as Fig. 3 and the least square method, the values of $\ln(I_{app}R_p)$ and $(R_pC_{dl})$ can be obtained. Since $I_{app}$ is already known, it means that we can obtain the values of $R_p$ and $C_{dl}$, respectively. After the value of $R_p$ is known, the corrosion current density is calculated from the Stern-Geary formula:

$$I_{corr}=B/R_p \tag{3}$$

where $I_{corr}$ is the corrosion current density, B is a constant (for active anode, B=26; for passive anode, B=52 [14,15].

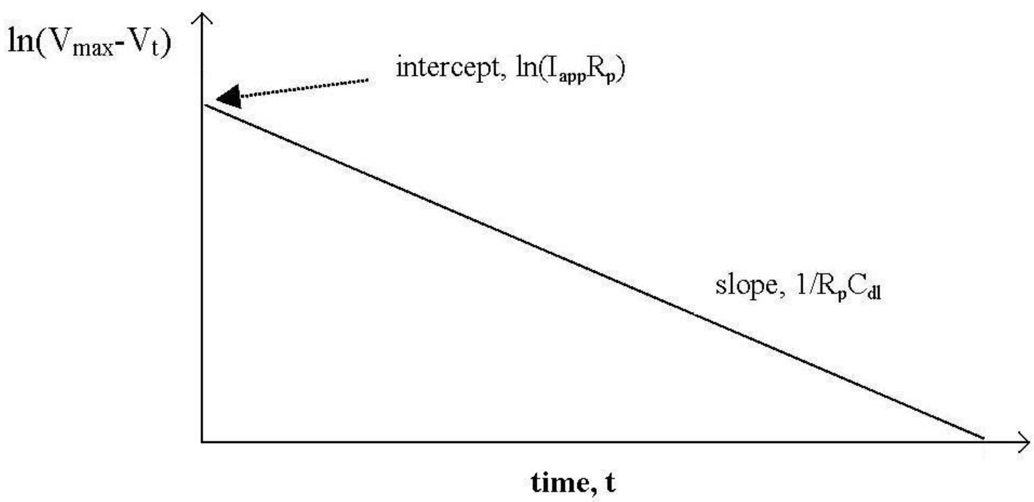


**Figure 3.** The logrithm of $V_{max}$-$V_t$ versus time.

Once again, since this method needs to know the half cell potential first the depolarization time is necessary for accurate and meaningful measurements. According to the suggestions from the manufacturer, the relations between the corrosion current density and corrosion status are tabulated in Table 2 [16].

**Table 2.** Relation between corrosion current density and corrosion status[16]

| Corrosion current density ($\mu A/cm^2$) | Corrosion rate (mpy) | Corrosion status |
|---|---|---|
| < 0.5 | < 0.23 | Ignore |
| 0.5 - 5 | 0.23-2.3 | Low |
| 5- 10 | 2.3-4.6 | Medium |
| 10-15 | 4.6-6.0 | High |
| > 15 | > 6.9 | Heavy |

## 3. RESULTS

### 3.1. Results of the first program

The test results for the first program were tabulated in Table 3. It can be seen that when no NaCl was added in concrete, corrosion statuses for pre-corroded part and control part (native, non-corroded) were negligible and the half cell potentials were noble, which indicated that the whole reinforcement had little chance in corrosion danger. Comparing the results of specimens with and without NaCl addition, it is found that while chloride contamination existed the corrosion possibility increased immediately. The half cell potential for pre-corroded part of reinforcement decreased from -64 mV(Ag/AgCl electrode) to -411 mV while the corrosion rate increased from 0.707 mpy to 2.751 mpy, whose corrosion status belonged to medium according to manufacturer's suggestions.

In addition, for specimens under the same conditions it can be found that water/cement ratios did influence the corrosion measurements. A lower water/cement ratio yielded a lower corrosion rate. The reason might be explained by the denser micro-structure induced by the lower water/cement ratio.

The above-mentioned results confirmed that the galvanostatic pulse technique with the guard ring could distinguish the local corrosion status provided only a single reinforcement was under the sensor.

**Table 3.** Test results for the first program

| Water/cement ratio | Reinforcement condition | NaCl addition in concrete | Corrosion rate (mpy) | Half-cell potential (mV) (Ag/AgCl electrode) |
|---|---|---|---|---|
| 0.6 | Corroded | No | 0.707 | -64 |
| 0.6 | Control | No | 0.172 | -55 |
| 0.4 | Corroded | Yes | 1.806 | -436 |
| 0.4 | Control | Yes | 0.067 | -90 |
| 0.6 | Corroded | Yes | 2.751 | -411 |
| 0.6 | Control | Yes | 0.182 | -104 |

### 3.2. Results of the second program

In the previous program, it has been confirmed that the galvanostatic pulse technique with the guard ring could distinguish the local corrosion status provided only a single reinforcement was under the sensor. However, to authors' best knowledge what we will obtain while multiple reinforcements are covered by the guard ring has not been investigated. Test results are depicted in Fig. 4.

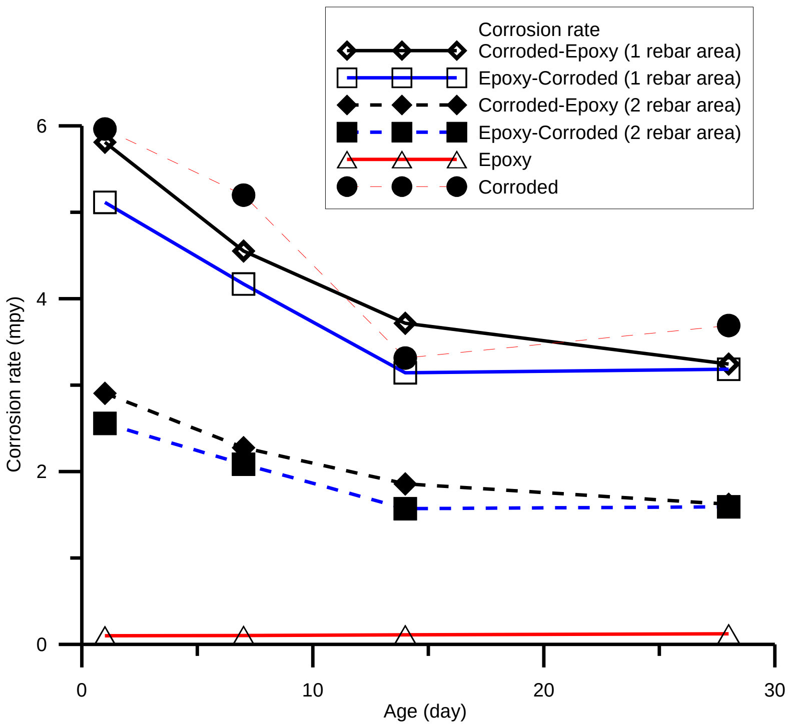


**Figure 4.** Corrosion rate measurements in the second program.

As mentioned earlier, four measuring configurations were conducted (corroded-epoxy, epoxy-corroded, epoxy and corroded). However, the counted reinforcement area affected the results. As seen in this figure, when one thought only the reinforcement near the guard ring was counted the counted reinforcement area only represent one reinforcement. In such a case, it could be found that one may obtain the corrosion rate close to the corroded reinforcement no matter which one was near the guard ring. It then may mislead us to overestimate the corrosion rate for epoxy-coated reinforcement.

On the contrast, if one considers all reinforcement areas should be counted. The results indicated that one may obtain an average value. Using this value may overestimate the corrosion rate of epoxy-coated reinforcement and underestimate the corrosion rate of corroded reinforcement.

When only one reinforcement was under the guard ring, the galvanostatic pulse technique could obtain the corrosion rate of each reinforcement no matter the reinforcement is corroded or epoxy-coated.

From the above results, one can conclude that when multiple reinforcements are under the guard ring the galvanostatic pulse technique may mislead us. Actually, the current measuring configuration is similar to the A-scan method in ultrasonic testing which reflects the signals for a 'line' under the sensor. To distinguish individual statuses for multiple reinforcements under the guard ring, the C-scan method in ultrasonic testing method may be one possible remedy.

## 4. CONCLUSIONS

In this article, the effects of multiple reinforcements on the corrosion rate measurements using the galvanostatic pulse technique with the guard ring were investigated. It is found when only one reinforcement was under the guard ring, the method could give the local corrosion rate. When multiple reinforcements were under the guard ring, the method then might give an average value provided all reinforcement areas were counted. And the method gave us the corrosion rate of the most dangerous one when only one reinforcement area was counted, this value could not be thought as the corrosion rate of the reinforcement near the guard ring. It is concluded the C-scan method which is commonly used in the ultrasonic testing may be one possible remedy to obtain the individual corrosion status when multiple reinforcements are used.

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