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Reliability of Galvanostatic Pulse Technique in Assessing the Corrosion Rate of Rebar in Concrete Structures: Laboratory vs Field Studies

R. Vedalakshmi*, L. Balamurugan, V. Saraswathy***, S.-H. Kim****, and K. Y. Ann*******

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Abstract

Corrosion of rebar in concrete structures is one among the various causes impairing its long-term durability. Precise assessment of corrosion rate (CR) is of prime importance to evaluate the structural safety as well as for estimation of service life of concrete structures. Among the electrochemical techniques, Galvanostatic Pulse Technique (GPT) is very promising for field mapping due to its rapidity. The reliability of GPT in determining the CR under passive and active state of rebar has been carried out using small size laboratory specimens and large scale aged concrete structures. The CR determined by the GPT is compared with the CR obtained by Electrochemical Impedance Spectroscopy Technique (EIST) and weight-loss method. The study reveals that an anodic pulse of 100 μA with a pulse duration of 10 seconds is able to determine the CR from 1-663 μm/y (from negligible to higher corrosion activity) on the rebar network more precisely even up to 65 mm of cover concrete. For instance the rebar corroding at higher rate, the CR predicted by GPT is very close to the CR by weight-loss method whereas it is 20 times less by EIST. In the case of passive state of rebar, the CR predicted by EIST is very close to weight-loss method whereas GPT predicts 10 times higher. In aged structures, the change in microstructure of concrete and loss of moisture from the concrete make the potential of rebar and resistivity of concrete more unpredictable and mislead the status of rebar embedded inside the concrete.

Keywords: *corrosion rate, galvanostatic pulse technique, electrochemical impedance, spectroscopic technique, frequency domain time domain, transient technique, weight-loss method*

1. Introduction

One of the electrochemical methods for determining the corrosion rate of steel in concrete is the measurement of polarization resistance (R_p). This relies on activation polarization, which is being the rate-determining factor in the anodic or cathodic process. Indeed it appears that in the majority of the cases monitoring data is influenced to a greater or lesser degree by the presence of diffusion polarization. Furthermore the overall polarization may result from a multiple step process. This has led to poor reproducibility in electrochemical data collected on the steel in concrete system leading to R_p may be overestimated. For determining the polarization resistance, among the electrochemical techniques linear polarization resistance method and Impedance method have been widely used (Feliu *et al.,* 1989; Mccarter *et al.,* 1990; Sagoe-crentsil *et al.,* 1992; Hachani *et al.,* 1994; Flis *et al.,* 1995; Jones *et al*., 1996; Grantham *et al.,* 1997; Zivica *et al.,* 2001).

Linear Polarization Resistance method (LPR) cannot separate the contributions of the various electrochemical processes involved such as charge transfer resistance, concentration polarization, interfacial layers or the ohmic resistance of the concrete. Additionally, the experimental method and associated execution parameters used (e.g., potential scan rate) will also have significant influence on the electrochemical response obtained.

Electrochemical Impedance Spectroscopy Technique (EIST), which involves measurement in the frequency domain, is a well established technique for identification of interfacial effects involved in the transfer of charge together with the detection of diffusional and electrolyte impedances. Though this technique eliminates some disadvantages as in the LPR method, it has also some drawbacks. Interpretation of data is difficult if the data appears to be incomplete and not unique to a single equivalent circuit. Dispersion of time constant causes depression of the

*Scientist, Corrosion Protection Division, Central Electrochemical Research Institute (CECRI), Karaikudi-630-006, Tamilnadu, India (E-mail: corrveda @yahoo.co.in)
**Graduate Student, Dept. of Civil and Environmental Engineering, Yonsei University, Seoul 120-749, Korea (Corresponding Author, E-mail: bala_cmme @yonsei.ac.kr)
***Scientist, Corrosion Protection Division, Central Electrochemical Research Institute (CECRI), Karaikudi-630-006, Tamilnadu, India (E-mail: corrsaras @yahoo.com)
****Member, Professor, Dept. of Civil and Environmental Engineering, Yonsei University, Seoul 120-749, Korea (E-mail: sanghyo@yonsei.ac.kr)
*****Member, Research Professor, Dept. of Civil and Environmental Engineering, Yonsei University, Seoul 120-749, Korea (E-mail: k.ann@yonsei.ac.kr)

Nyquist plot. Concentration effects associated with the Warburg Impedance, which mask polarization resistance. It requires the collection of data at low frequencies, which leads to larger measurement times and significant electrode disturbance both of which are unsuitable for practical on-site monitoring.

Considering the uniqueness of the steel in concrete system as an electrochemical entity and the system was strongly influenced by chloride concentration gradient, it is more appropriate that instantaneous corrosion rate measurement must be kept as short as possible. For this, Galvanostatic Pulse Technique (GPT) has been introduced for laboratory as well as field application. It is a transient technique, which involves measurement in the time domain. The theory suggests that galvanostatically induced potential-time transient method can provide the polarization resistance from the measurement of a time constant and a knowledge of the double layer capacitance per unit area. Monitoring potential is expected to be insensitive to steel area and because of this, this method prove to be an advantage when dealing with an unknown or variable steel area.

(Newton *et al.,* 1988) reported that the time constant and diffusion behaviour of rebar can be done more easily using GPT than by EIST. (Glass *et al.,* 1997) compares the R_p and C_{dl} values determined using current transient method with potential transient method and found values are higher using the former. (Gonzalez *et al.,* 2004) also investigated the influence of Counter Electrode (CE) on I_{corr} values using GPT as well as EIST and inferred that I_{corr} by GPT is not affected by the size of CE whereas the values differ by 2 to 5 times in EIST. (Basseler *et al*., 2003) determined the I_{corr} using GPT and compared with the weight-loss measurement and inferred that when the rebar is in active condition I_{corr} was 3.6 μA/cm^2 and it was 5.4 μA/cm^2 using weight-loss measurements. Whereas when the rebar is in passive condition, 1.8-2.7 times difference between them was obtained. (Sathyanarayanan *et al*., 2006) correlated the corrosion rate determined by LPR, GPT with the gravimetric method and inferred that compared to LPR method, corrosion rate by GPT was very close with the weight-loss method. The data obtained from on-site and laboratory measurements by Gulikers *et al*., (2003) Reported that the GPT is not able to make a clear distinction between passive and actively corroding rebars. Corrosion rates derived for passive steel seem to be unrealistically high, i.e., frequently exceeding 1 μA/cm^2. Gonzalez *et al*. (2001) found in large reinforced concrete structures use of an estimated value of C (capacitance) per unit area in GPT lowers its reliability when the size of CE used is smaller than the rebar. Frouland *et al.* (2002) and Biegovic *et al*. (2004) used GPT to assess the rebar in various structural elements such as bridge pillars, beams, deck slabs and found that the CR determined by GPT is in close agreement with the actual section-loss.

From the earlier investigation the reliability of predicting the corrosion rate of rebar is not established and the data is spare on the effect of cover on the magnitude of pulse and pulse duration. The paper discusses the accuracy of GPT technique in assessing the corrosion rate of rebar by comparing with the EIS and weight-loss method. In addition to small-scale laboratory specimens, studies were carried out on large scale slab as well as on concrete structures.

2. Experimental Investigations

2.1 Laboratory Studies

2.1.1 Accelerated Corrosion Test on RCC Cubes – Specimen Preparation

One hundred fifty mm size cubical specimens were cast using the mix proportion of 1: 2.19: 3.73 with w/c ratio of 0.5. Ordinary Portland cement was used for casting the concrete specimens. Well graded river sand and good quality crushed blue granite were used as a fine and coarse aggregates respectively. 10 mm dia. rebars having a length of 10 cm was embedded at 25, 40 and 50 mm cover respectively. Initial weights of the rebar were recorded. While casting all the three rebars were embedded vertically with a 25 mm cover both at the top and bottom. For electrochemical measurement, copper wire was brazed at one end of the rebar and that was sealed. Measurement was carried out over an exposed length of 8 cm and the remaining area was sealed using araldite. Potable water was used for casting the concrete specimens. Duplicate specimens were cast and cured for 28 days in potable water. In one set of specimen, the passive state of rebar was maintained as such after curing of the concrete specimens whereas in another set of specimen active state of rebar was induced by conducting the accelerated corrosion test in 3% NaCl solution. A PVC bund of 5 cm depth was fixed on the one side of specimen below which the rebar was embedded and 3% NaCl solution was ponded. Using stainless steel electrode as an auxiliary electrode and rebar as a working electrode, impressing an anodic current of 350 μA /cm^2 for a period of 1, 2, 4 days, the different rate of corrosion was induced from low to highest corrosion rate on rebar embedded at different covers. Rate of corrosion was determined at the end of 1, 2, 4 days using Electrochemical Impedance Spectroscopic technique (EIS) and Galvanostatic Pulse Technique (GPT).

2.1.2 Corrosion Rate Measurements on RCC (Reinforced Cement Concrete) Slab - Specimen Preparation

RCC slab of size 1.0×1.0×0.075 m has been cast using the mix proportion of 1:1.76:2.05 with w/c ratio of 0.50 after leaving the portion of 0.4×0.4×0.075 m. Inside the slab, 10 mm dia. reinforcement cage with c/c spacing of 18 cm. was embedded at 25 mm cover from the top of the slab. After 24 hrs of casting, the portion of the slab, which was left, filled with chloride contaminated concrete using the same mix proportion. 1.2 % chloride by weight of cement was added along with the concrete at the time of casting and cured for 28 days. The rebar area (251 cm^2) under chloride contaminated concrete acted as an anode and the rebar area (1256 cm^2) under uncontaminated concrete was acted as cathode. By forming a macro galvanic couple in the ratio of 1:5 on the reinforcement cage, the corrosion was accelerated on the rebar under anodic area. When making CR measurement, the slab was divided into 5 grid points at 18 cm c/c spacing. Rate of corrosion was assessed under passive and active zone of rebar using Galvanostatic Pulse Technique (GPT) only. Corrosion rate measurements were carried out only on the top mat of the reinforcement cage and the guard ring probe was placed between the two rebar to avoid junction points.

2.1.3 Method of Measurement - Electrochemical Impedance Spectroscopy Technique (EIST)

The potential of the rebar was measured periodically using a high input impedance multimeter. Saturated calomel electrode was used as a reference electrode. Impedance measurement was made using three electrode arrangements. Stainless steel electrode of size Ø10 mm×90 mm was used as an auxiliary electrode and saturated calomel electrode was used as a reference electrode. Rebar embedded in concrete acted as a working electrode. The electrode assembly was kept on a wetted sponge. The length of the counter electrode is more than the exposed length of the rebar and by means of this, current was distributed uniformly throughout the length of the rebar. Chloride solution was used as a contacting solution to reduce the contact resistance between the electrode assembly and the concrete. A small sinusoidal voltage signal of 20 mV was applied over a frequency range of 100 KHz to 10 mHz using a computer controlled electrochemical analyzer (Model 6310: E G & G Instruments, Princeton applied research). Measurements were made periodically. The impedance values were plotted on the Nyquist plot. Using the software 'Z view' by extrapolating the low frequency arc in the frequency range between 100 Hz to 10 mHz, the R_p value was determined.

From the R_p values, by assuming B as 26 mV, the I_{corr} was calculated using the Stern- Geary relation as follows:

$$I_{corr} = \frac{R}{R_p} \tag{1}$$

Where, B = Stern-Geary Constant, 26 mV for both active and passive state of rebar

R_p = Polarization resistance, ohms-cm^2

I_{cor} =Corrosion current, μA/cm^2.

From the $I_{corr,}$ the Corrosion Rate (CR) of rebar was calculated using the following formula,

$$Corrosion\ rate,\ \mu m/y = 11.6 \times I_{corr} \tag{2}$$

2.1.4 Galvanostatic Pulse Technique (GPT)

GalvaPulse' model No.GP5000 (Gremann Instruments, A/S. Denmark), uses a transient technique for measuring the R_p. The transient technique assumes that a simple Randles describes the potentiostat response of the steel-concrete system as a function of time when a galvanostatic current is applied. Two circular zinc electrode rings are used in the electrode assembly of the Galvapulse: a counter and a guard ring with outer/inner diameters of 60/30 and 100/86 mm, respectively. The electrode rings are positioned concentrically with an Ag/AgCl reference electrode in the centre.

Since the length of the rebar embedded inside the concrete cube was known, the guard ring probe was kept on 'OFF' position when making measurement. When no current confinement is used, the guard ring is deactivated and the current is only applied from the inner electrode ring A galvanostatic pulse of 100 μA with a pulse duration of 10 seconds was applied for both passive and active condition of rebar. The pulse produces a transient change in the potential of the rebar in the anodic direction, which is continuously monitored using Ag/AgCl reference electrode. In the beginning, the potential changes were recorded with 27 msec (approximately 50 readings) followed up by 125 msec between the remaining measuring points. All the data were collected in the data logger and then analyzed by specially developed software in a psion computer. The instantaneous potential following current switch-on is assumed to be the ohmic drop over the concrete electrolyte. Detailed numerical analysis of the measurement data using linearization technique allows the determination of polarization resistance and hence the corrosion rate to be calculated (Gonzalez *et al.,* 2001; Frolund *et al.,* 2002). Using Stern-Geary constant as 26 mV, the corrosion rate was displayed directly. When measuring on the slab and field structures, the guard ring probe was kept 'ON' position to confine the electrical signal to the length of 7 cm (diameter of inner guard ring) on the rebar. The CR of the rebar in RCC slab was determined only by using GPT. The collected data was presented as potential, CR and resistance contours.

2.1.5 Weight-Loss Method

After the application of current over a period of 4 days, the specimens were exposed under laboratory conditions for a period of 90 days to conduct GPT and EIST measurement. Then the concrete specimens were broken open and the rods were visually examined for the extent of rust. After pickling the rebars in inhibited hydrochloric acid as specified in (ASTM G1-90., 2000), the final weight was measured. From the initial and final weight, the corrosion rate in mmpy was calculated as:

$$Corrosion\ rate\ in\ \mu m/y = \frac{87600 \times W}{DAT} \tag{3}$$

Where, W=loss in weight, mg; D=Density of Iron, gm/cm^3; A= Area, cm^2; T=Time, hrs

The corrosion rate obtained from EIST and GPT were compared with the rate obtained from gravimetric method.

2.2 Field Studies

Using GPR the CR of rebar embedded in large scale field structures was monitored. They are presented as case studies and describe as below:

2.2.1 Case Study 1

Structural Details : RCC slab

Size : 1.58×1.58×0.1 m

Cover : 65 mm
Exposure Condition : Under mild exposure
Period of Exposure : 4 years
Grade of Concrete : 20 MPa

2.2.2 Case Study 2

Structural Details : RCC roof slab
Cover : 25 mm
Grade of Concrete : Un known
Exposure Condition : Exposed to magnesium sulphate
: environment for a period of 25 yrs.

2.2.3 Case Study 3

Structural Details : Sun Shade
Size : 0.45×0.75×0.20 m
Grade of Concrete : Un known
Exposure Condition : 30 yrs of exposure under seepage of
: water during rainy season due to
: Improrper drainage

3. Results

3.1 Potential

As per (ASTM C 876 - 09, 2001) the following criteria have been applied while interpreting the data.

Table 1. Potential, mV vs Ag/AgCl

Potential, mV vs SCE	Potential, mV vs Ag/AgCl	Probability of Corrosion (%)
More –ve than -275	More –ve than -255	.> 90 (active)
Between -275 to -125	Between -255 to -105	Uncertain
More + ve than -125	More + ve than -105	< 10 % (passive)

Table 2 compares the potential of rebar at passive and active conditions. It is observed that as per ASTM C876, if the potential value is less than -255 mV vs Ag/AgCl (potential difference between SCE and Ag/AgCl is -20 mV) rebar is in passive condition. After one day application of current, the potential value of rebar at 25 mm cover reaches to -397 mV indicates that the rebar gets corroded whereas at 40 and 50 mm cover the value is -146 and -127 mV which is less than -255 mV and denotes that the rebar is still in passive condition. Similar trend is observed at the end of 2 days of application of current. But at the end of 4 days of application of current, the rebar at 25 and 40 mm cover shows active potential value of–287 mV, -304 mV Vs Ag/AgCl respectively and at 50 mm it still shows a passive potential value of -183 mV. The potential data clearly indicates that the rebar at 25, 40 mm cover get corroded whereas at 50 mm cover still maintains the passive condition.

3.2 Corrosion Rate (CR)

3.2.1 Electrochemical Impedance Spectroscopy Technique

Figs. 1(a)-(d), show the Nyquist behaviour of rebar in passive as well as in active condition. Invariably in all the Nyquist plots obtained two arcs are present. One arc at high frequency region (100 kHz-10 mHz) and another arc at low frequency region (100 Hz-10 mHz). Frequency above 1 Hz reflected mainly the conductance properties of the concrete and was hardly influenced by the charge transfer resistance of rebar. Hence the changes occur at the steel-concrete interface can be easily identified from the changes in the low frequency curve. By extrapolating the low frequency curve as a straight line to the real axis, the slope of the curve was obtained and given in Table 3, From the Table, it can be seen that when the rebar is in passive condition, the slope of the arc varies from -2.94 to - 4.09 and indicates that the rebar is under purely capacitive bahaviour. With an application of current, when corrosion activated on the rebar, the slope of the low frequency arc start to decrease and attains a perfect semi-circle with a slope value of 0 when corrosion spreads uniformly throughout its length. For example, the slope of the low frequency arc decreases to 0 at 25 mm cover at the end of 1 day application of current. Whereas the value is -3.93, -1.29 and 0 at 40 mm cover; -5.49, -2.70 and 0 at 50 mm cover at the end of 1, 2 and 4 days of application of current respectively. From the slope value it can be inferred that at 25 mm cover, the corrosion spreads uniformly after 1 day application of current whereas in the case of 40 and 50 mm cover it happens only after 4 days. It emphasis that the passive, initiation of corrosion and uniform corrosion of various stages occurred during the corrosion process on the rebar can be easily identified from the change in slope of the low frequency arc in EIST.

The CR of rebar determined using EIST at various cover is compared in Table 3, From Table 3, it can be seen that at passive

Table 2. Comparison of Rebar Potential

Cover of Concrete (mm)	Potential, mV							
	Passive Condition of Rebar		Active Condition of Rebar					
			After 1 day Application of Current		After 2 days Application of Current		After 4 days Application of Current	
	GPT Vs Ag/AgCl	EIST Vs SCE	GPT Vs Ag/AgCl	EIST Vs SCE	GPT Vs Ag/AgCl	EIST Vs SCE	GPT Vs Ag/AgCl	EIST Vs SCE
25	-240	-234	-397	-491	-396	-518	-287	-332
40	-223	-320	-146	-246	-154	-313	-304	-367
50	-171	-291	-127	-230	-132	-203	-183	-288

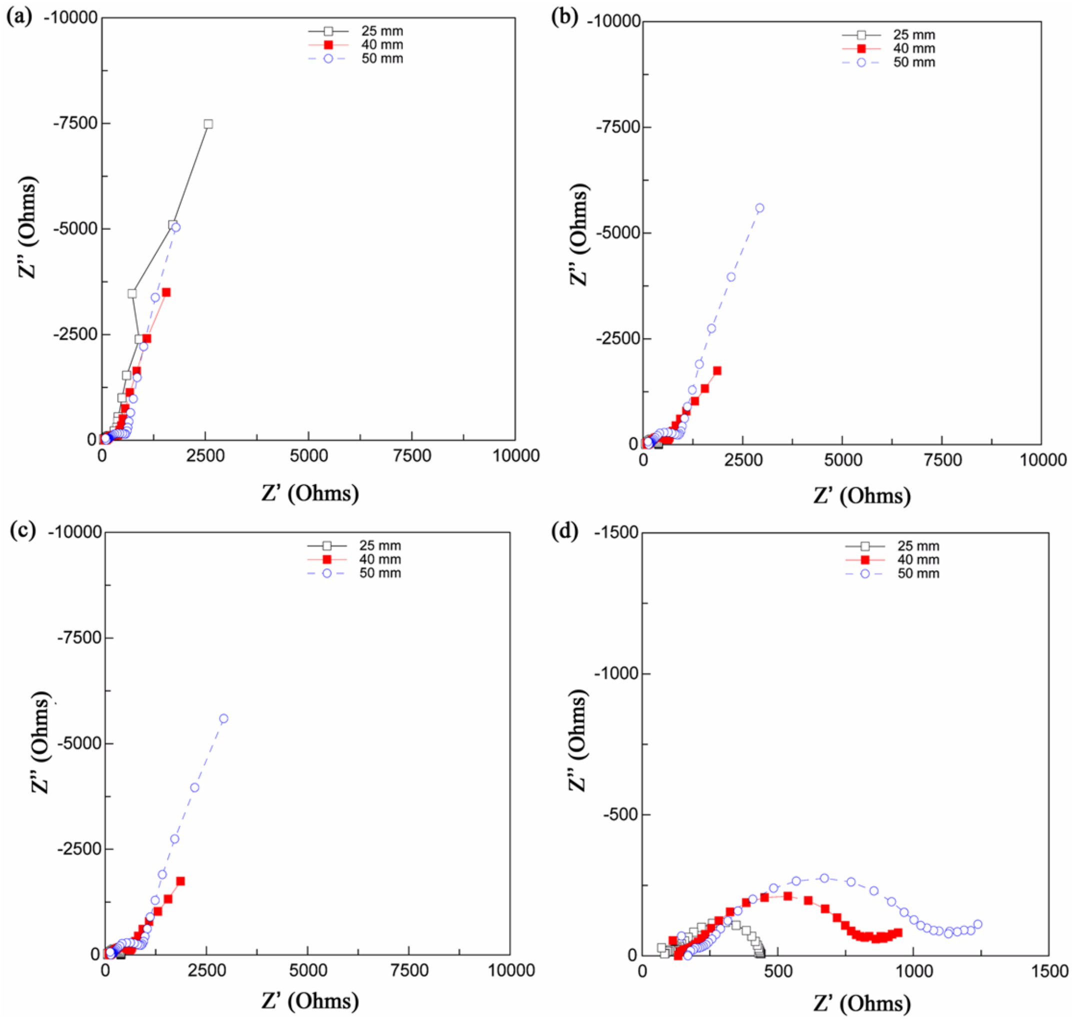

Fig. 1. Nyquist Behavior of Rebar at Various Stages of Corrosion: (a) Passive, (b) After 1 day Application of Current, (c) After 2 days of Application of Current, (d) After 5 days of Application of Current

Table 3. Comparison of Corrosion Rate

Cover of Concrete (mm)	Corrosion Rate, μm/y											
	Passive			Active								
				After 1 day Application of Current			After 2 days Application of Current			After 4 days Application of Current		
	GPT	EIST	Slope of Low Frequency Arc	GPT	EIST	Slope of Low Frequency Arc	GPT	EIST	Slope of Low Frequency Arc	GPT	EIST	Slope of Low Frequency Arc
25	1.6	0.8	-3.09	258	30.7	0	890.5	34.9	0	662.8	34	0
40	1.9	0.3	-2.94	2.2	1	-3.93	2.9	6	-1.29	85.3	16.1	0
50	1.9	0.2	-4.099	2	1	-5.49	2.1	2	-2.70	27.7	12	0

condition, a very negligible CR in the range of 0.2-0.8 μm/y is obtained. At active state of rebar, the CR increases with an application of current. At 25 mm cover, it reaches a maximum value of 34.9 μm/y after 2 days application of current and reduces to 34 μm/y at the end of 4 days. The corrosion product formed on the rebar reduces the rate of corrosion after 2 days.

3.2.2 Galvanostatic Pulse Technique (GPT)

Using GPT, the CR of passive and active condition of rebar is compared in Table 3, from the table it is observed that the CR is 1.6, 1.9 and 1.9 μm/y at 25 and 40, 50 mm cover respectively. When corrosion is accelerated, at 25 mm cover, the CR is 662.8 μm/y at the end of 4 days. At 40 and 50 mm cover, the CR is 7.7 and 24 times less than that of 25 mm cover.

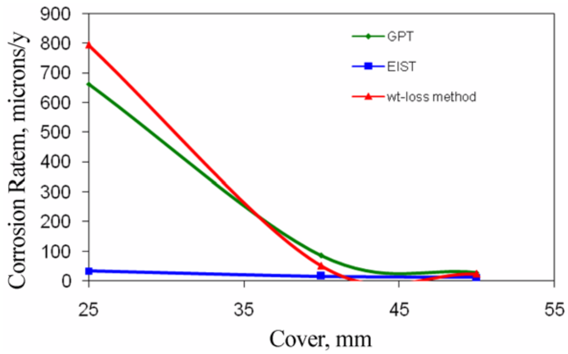

Fig. 2. Comparison of Corrosion Rate: GPT & EIST vs Weight-Loss Method

3.3 Comparison of CR by GPT & EIST Vs Weight-Loss Method

From Table 3, it can be seen that under passive condition, the CR predicted by EIST is 2, 6.3 and 9.5 times less than that of GPT at 25, 40 and 50 mm cover respectively. Under passive condition, since the CR is 0 mmpy by weight-loss method, it appears that the CR measured by EIST is very closer with the weight-loss method than the CR by GPT and could be inferred that EIST is more accurate in predicting the lower corrosion rate. But under active condition, the CR predicted by EIST is less than by GPT at every stages of corrosion.

Fig. 2, compares the CR of rebar under active condition (after 4 days of application of current) using GPT and EIST with weight-loss method. From the Figure it is clearly observed that the CR by GPT is nearing very near to the CR by weight-loss method invariably at all covers and hence compared to EIST, GPT predicts the CR more accurately. The current pulse of 100 μA is sufficient to determine the CR from low corrosion activity to high corrosion activity even when the rebar is at 50 mm cover.

3.4 Corrosion Rate Measurements on RCC Slab

The contours given in Figs. 3, 4 and 5, compare the potential, corrosion rate of rebar and resistance of concrete respectively by using Galva pulse at the end of 2 months and 14 months. From Fig. 3(a), it can be seen that initially the rebar in chloride-contaminated concrete (from grid point X, Y; 4, 1; 5, 1) shows active potential value which is in the range of -300 to -350 mV. The rebar embedded in the adjoining area to chloride-contaminated concrete also shows more -ve value in the range of -250 to -300 mV. In the case of chloride free concrete it is in the range of -100 to -150 mV, which is less than the threshold potential value of -275 mV indicates that the rebar is in passive condition. But after 14 months of exposure [Fig. 1(b)], the potential value of the rebar in chloride contaminated concrete shifts to less -ve value in the range of -200 to -250 mV. Initially the availability of free chloride and moisture is more; with time the free chloride react with C_3A phase present in the concrete and bound as Friedel's salt. This may be the reason for showing less negative potential. Since the atmospheric exposure site is mild environment, the internal chloride only caused corrosion of rebar rather than from the external chloride. Reduction of moisture and chloride in the concrete with time caused to shifts the potential to less –ve value.

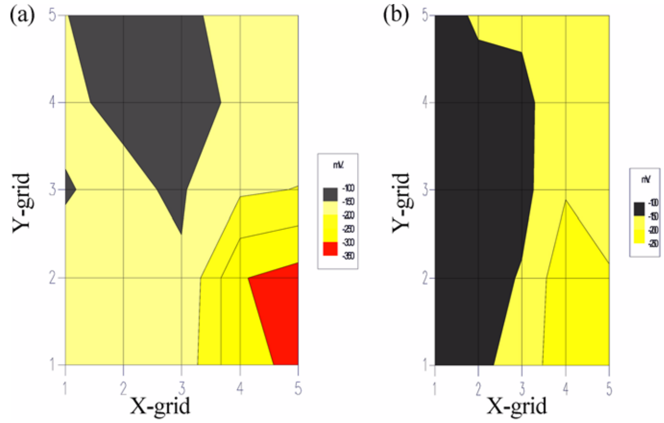

Fig. 3. Potential Contours of RCC Slab: (a) Potential-After 2 Months, (b) Potential-After 14 Months

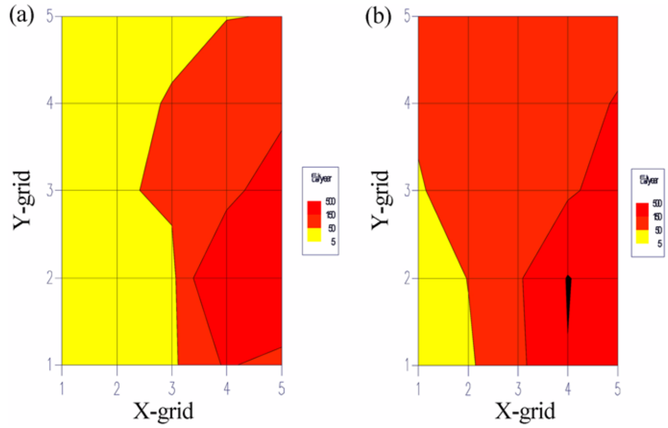

Fig. 4. Corrosion Rate Contours of RCC Slab: (a) Corrosion Rate-After 2 Months, (b) Corrosion Rate- After 14 Months

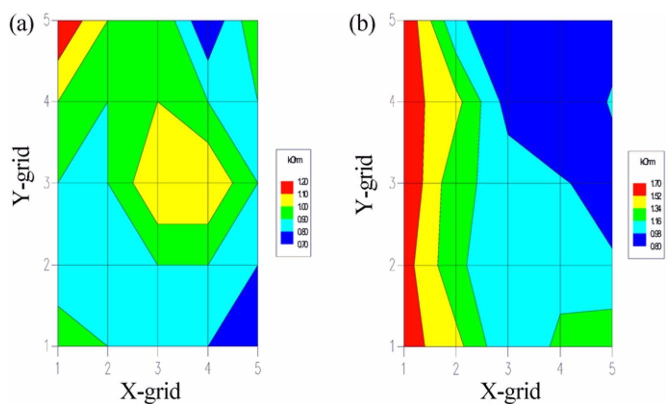

Fig. 5. Resistivity Contours of RCC Slab: (a) Resistivity-After 2 Months, (b) Resistivity- After 14 Months

Figs. 4(a) and (b), compares the corrosion rate contour of RCC slab at the end of 2 and 14 months. In contrary to the potential measurements, compared to 2 months of exposure, the corrosion rate of rebar spreads to a larger area after 14 months. The contour also emphasis that once corrosion is initiated on the rebar it spreads to the adjoining area after forming a macro galvanic couple irrespective of amount of chloride present near the rebar. It is also inferred that in galvanic corrosion the area of anode: cathode ratio is the rate determining factor rather than the amount of chloride. Because in presence of chloride, after forming a ferric chloride the chloride has been released as given in eqns:

$$Fe \rightarrow Fe^{2+} + 2e^{-} \ (anodic\ reaction) \quad (4)$$

$$Fe^{2+} + 2Cl^{-} \rightarrow FeCl_2^{-} \quad (5)$$

$$FeCl_2 + 2H_2O \rightarrow Fe(OH)_2 + 2HCl \quad (6)$$

From Eq. (6), it can be seen that after forming $Fe(OH)_2$, the chloride ions released back to pore solution, to complex more Iron and thus chloride essentially acts as catalyst in corrosion reaction in presence of chlorides. Though the available free chloride ions are decreased with time, the chloride ions reacted is released because of catalytic reaction in nature, the corrosion spreads on the rebar embedded in chloride contaminated concrete. The portion of rebar embedded in chloride contaminated concrete act as an anode whereas the rebar embedded adjoining to it act as cathode and due to macro galvanic corrosion, the corrosion spreads to the rebar embedded in the area adjoining to the chloride contaminated concrete. The CR of rebar is maximum in the range of 150-500 µm/y in chloride contaminated concrete and gets reduced to 50-150 µm/y to the adjoining area. From Fig. 3(b), it can be seen that small area spanning from the grid point1-2, is having negligible CR in the range of 5-50 µm/y whereas the remaining area of the slab is under high corrosion activity.

Figs. 5(a) and (b), show the resistivity of the RCC slab at the end of 2 and 14 months respectively. From the contour it is seen that the initial resistivity value of 0.7-0.9 kΩ-m in chloride added concrete after 2months has been increased to 0.8-1.1 kΩ-m at the end of 14 months. It seems reduction of moisture and chloride with time increases the resistance value but does not influence the CR significantly. In the case of chloride free concrete, compared to 2 months of exposure, the high resistance value of concrete i.e. 1.3-1.7 kΩ-m has been spread to the larger area at the end of 14 months of exposure due to considerable loss of moisture from the slab and micro structural changes occurred in the concrete with time.

3.5 Field Studies

As reported in earlier investigations (Frolund *et al.,* 2002), the following criteria have been applied while interpreting the corrosion rate data collected from the field measurement.

Table 4. Active/Passive Conditions of Rebar

Corrosion rate (µm/year)	Condition of rebar
5.8	Passive
5.8-23	Negligible corrosion activity
23-58	Low corrosion activity
58-174	Moderate corrosion activity
>174	High corrosion activity

3.5.1 Case Study 1

Figs. 6(a), (b) and (c), compare the potential, corrosion rate and the resistance of the RCC slab as described in the case study No.1. From the potential and corrosion rate contours, it can be clearly observed that the area which is having the active potential value in the range of -250 to -350 mV recorded a maximum CR of 50-150 µm/y and comes under moderate corrosion activity. From the CR contours, the area up to which the maximum and minimum CR recorded was marked on the slab. Then the slab was broken at these two places and the rebar under these two marked areas were visually examined. The extent of rust on the rebar observed is given in Figs. 7(a) and (b). Fig. 7(a), clearly shows if the CR is 50-150 µm/y, there is rust on the rebar whereas if the CR is 5-50 µm/y, no corrosion was observed on the rebar. According to the criteria given in the above Table, the CR in the range 5-50 µm/y comes under negligible to low corrosion activity and hence the rebar maintains the passive condition.

3.5.2 Case study 2

Figs. 8(a), (b) and (c), show the contours of roof slab as described in case study 2. Though the rebar of roof slab is under severely deteriorated condition due to magnesium sulphate, the potential value of the rebar as given in Fig. 8(a), is less than -200 mV. when comparing the potential value with the CR, the region which shows potential less than -150 mV shows highest CR in

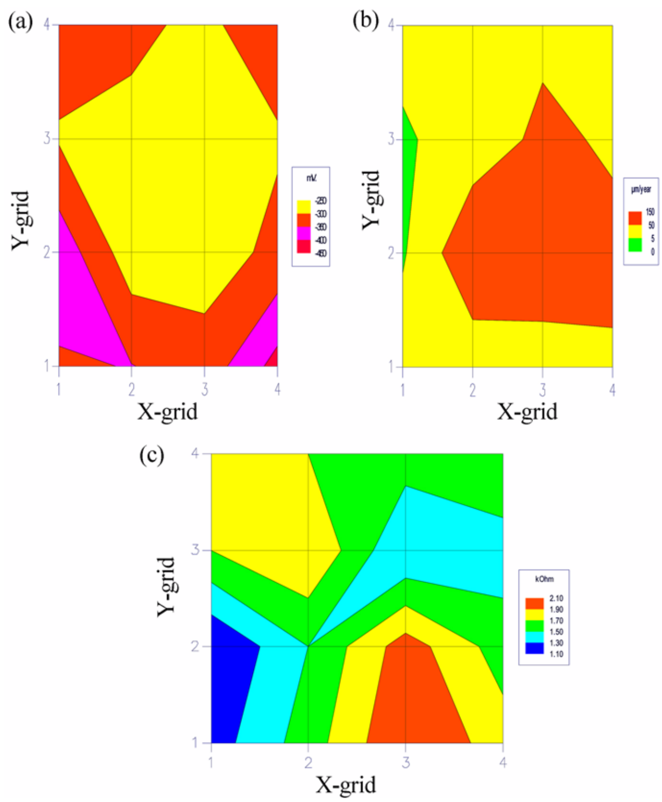

Fig. 6. Contours of Slab Described in Case Study 1: (a) Potential, (b) Corrosion Rate, (c) Resistivity

Fig. 7. Extent of Rust on the Rebar (Case Study 1): (a) Maximum Corrosion Rate, (b) Minimum Corrosion Rate

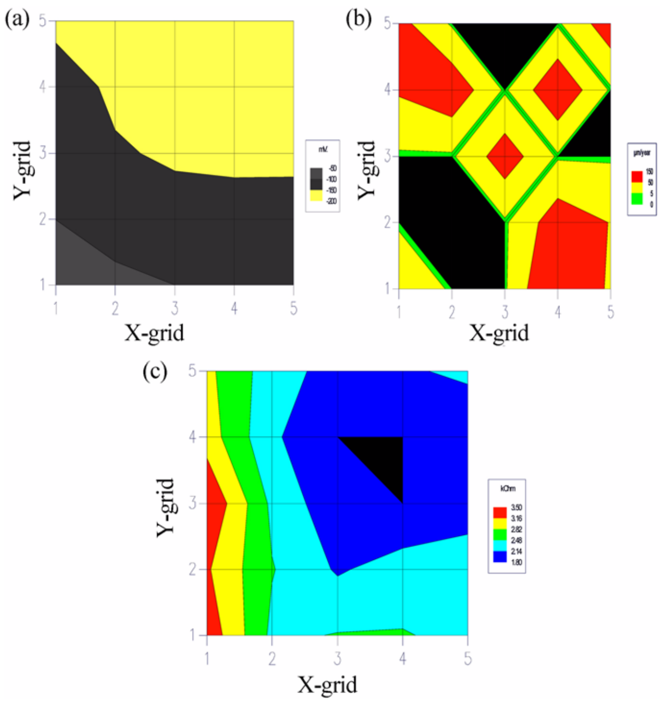

Fig. 8. Contours of Slab Described in Case Study 2: (a) Potential Contour, (b) Corrosion Rate Contour, (c) Resistivity Contour

the range of 50-100 μm/y which comes under moderate corrosion activity. In aged structures, the potential measurement of rebar is not able to indicate the actual condition of the rebar more precisely. From Fig. 8(c), it can be seen that the region which is having maximum CR of 50-150 μm/y, the resistance of the concrete is in the range of 1.8-2.48 kΩ-m. It is comparatively lower than the region which shows CR in the range of 5-50 μm/y where the resistance value is in the range of 2.82-3.50 kΩ-m.

3.5.3 Case Study 3

Improper drainage of rain water causes severe corrosion of rebar in sunshade as given in Figs. 9(a), (b) and (c), show the

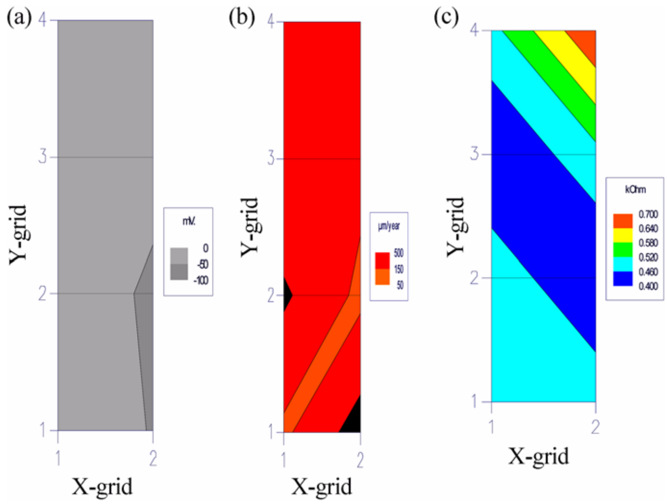

Fig. 9. Contours of Sunshade as Described in Case Study 3: (a) Potential Contour, (b) Corrosion Rate Contour, (c) Resistivity Contour

potential, CR and resistance contour of the sunshade respectively. From Fig. 9(b), it can be seen that CR of rebar embedded inside the sunshade is in the range of 150-500 μm/y which comes under high corrosion activity but the potential values are less than -100 mV [Fig. 9(a)], The resistivity of the concrete recorded a very low value in the range of 0.4-0.7 kΩ-m. The CR and the resistance of the concrete clearly indicate the severely rusted condition of the sunshade. In aged structures, the loss of moisture from the concrete introduces lack of continuity in the pore channel which impedes the diffusion of ions and due to this the potential of the rebar is not able to predict the actual status of rebar.

4. Discussion

The use of half-cell potential measurements to determine the corrosion risk of reinforcing steel in concrete has been widely used since 1970 (Feliu *et al.,* 1989; Sagoe-crentsil *et al.,* 1992; Flis *et al.,* 1995; Grantham *et al.,* 1997; Zivica *et al.,* 2001). Potential readings however do not provide information on the corrosion rate of the reinforcement. The potential measurement on the concrete surface shows that despite the simple measuring procedure, the results of potential mapping need careful interpretation. The concrete cover depth, resistance of the concrete, high resistive surface layer and polarization effects are greatly influence the measured potential values. In addition to this, the surface wetness during the E_{corr} measurement has a greater influence particularly when the rebar is under active state whereas under passive state its influence is insignificant (Gonzalez *et al.,* 2004). Continuous wetting of the structural components is not possible when making field measurement to make E_{corr} more reliable. (Broomfield *et al.,* 1991) reported that the potential measured by reference electrode is not true E_{corr}, but rather a mixed potential of unknown area of the rebar. Liquid junction potential, variation in pH and oxygen concentration in the cover concrete posed a greater error by keeping the reference electrode on the concrete surface (Myrdal *et al*., 1997, 1998). Table 4 compares the rebar potential with CR, compares the potential of the rebar with CR. From the data it is clearly evident that under laboratory condition, if the potential increased from -150 mV to -350 mV from passive to active, the CR increased from 150 to 500 μm/y respectively. Under field condition, as given in case study 2, the potential of the rebar is in the range of 0 to -100 mV indicates that the rebar is in passive condition; but CR is in the range of 150-500 μm/y indicates that the rebar gets severely corroded. Hence on aged structure the potential measurement is not reliable and I_{corr} measurement is the only fool proof technique to assess the condition of the rebar. GPT is a transient technique which is able to measure the CR less than 30 seconds and does not require longer stabilization time as in linear polarization resistance measurement. At site, where large numbers of measurements have to be carried out, the Galva pulse produced a very much faster output.

4.1 Resistance of Concrete

It is well-known that the rate of corrosion of steel in concrete is mainly dependent on the ionic conductivity of concrete electrolyte, its humidity, temperature and the quality of cover concrete. The ionic conductivity of the concrete is measured quantitatively as resistivity of the concrete. But in the present study, using galvapulse, the resistance was measured between the concrete surface and the bar using two probe technique as ohmic resistance. It was calculated after extrapolating the potential-time response to time zero (Elsener *et al.,* 2005). High w/c ratio, chloride bearing, saturated concrete provides the lowest resistance, while low w/c, well cured and dry concrete provides the highest. While interpreting the results of field data, if the resistance is less then the rebar inside that concrete is in corroding condition. For example, from Fig. 5(b), it can be seen that the slab which is exposed under laboratory condition, the region at which CR is 150-500 μm/y, then the resistance value is less than 1.16 kΩ. In this case there is a good correlation between resistance and corrosion rate mapping.

4.2 Magnitude of the Pulse

Selection of magnitude of perturbing signal and duration of pulse to be applied is a critical parameter in assessing the CR using GPT. Measurements carried out in a shorter period contain too little information to know the electrochemical behaviour and to estimate the CR. The magnitudes of the pulse do discriminate between high and low corrosion rates, provided that the current used is correctly adopted. Too low current make it difficult to separate the polarization response from back ground noise. Higher current improve pulse transient but may shift the potential in the non-linear region. Stern-Geary equation requires linearity of the potential/current relationship, and this is not occurred if large perturbation was used. Table 6(a) remains unchanged and (b), compares the magnitude of the pulse on the I_{corr} of rebar when the rebar is in passive and active condition. When measuring the I_{corr} of rebar at passive state, it lies between 0.1293-0.1552 μA/cm^2 by changing the magnitude of the pulse from 8-100 μA. Change in I_{corr} is not significant and appears that the magnitude of the pulse shall be minimum of 100 μA with a pulse duration of 10 secs is sufficient. (Videm *et al.,* 1996) reported the passivation current density of iron in alkaline solution is less than 0.2 μA/cm^2 and observed it was independent of potential and pH. The obtained I_{corr} value is less than the reported value and ensures that the rebar is in passive condition. But from Table 6(b), when the rebar is in active state, the I_{corr} is increased from 29.03 μA/cm^2 to 62.02 μA/cm^2, if the magnitude of the pulse increased from 100 to 300 μA. There is 2 times increase in I_{corr} if the current pulse is increased by 3 times. Because of the higher interfacial capacitance at higher anodic pulse higher, I_{corr} was recorded. From the weight loss data, it can be concluded that the I_{corr} predicted at 100 μA anodic pulse is very close to the actual value.

From the above discussion it can be inferred that 100 μA of anodic with a pulse duration of 10 secs is sufficient to measure the lowest CR of 0 μm/y to highest CR of 662.8 μm/y, i.e., from non-corroding to highly corroding condition of rebar under both laboratory as well as field conditions. From Table 6, it can be

Table 5. Comparison of Rebar Potential vs CR

Potential Range (mV Vs Ag/AgCl))	Corrosion Rate (μm/y)	
	Laboratory Results	Field Measurement
-300 to-350	150-500	–
-250 to -300	50-150	50-150
-200 to -250	150-500	
-200 to -150	50-150	50-150
0 to -100	–	150-500

Table 6(a). Comparison of Corrosion Rate vs Pulse Width at Passive Condition of Rebar

Anodic Pulse (μA)	Pulse Duration (sec)	I_{corr} (μA/cm^2)	Corrosion Rate (μm/y)
8	10	0.1466	2.0
25	10	0.1466	1.7
50	10	0.1293	1.5
100	10	0.1552	1.8

Table 6(b). Comparison of Corrosion Rate vs Pulse Widths at Active Condition of Rebar

Anodic Pulse (μA)	Pulse Duration (sec)	I_{corr} (μA/cm^2)	Corrosion Rate (μm/y)	Corrosion Rate (μm/y) (from Wt-Loss Method)
100	10	29.03	336.7	224.2
200	10	51.344	595.60	----
250	10	58.308	676.4	-----
300	10	62.02	719.4	-----

seen that the lowest CR that can be able to measure using GPT is 1 μm/y. From the laboratory as well as field data even upto 65 mm cover of concrete, a current pulse of 100 μA is sufficient to locate the active and passive area in the rebar net work. Guard ring probe is able to confine the electrical signal on the rebar to the length of diameter of smaller counter electrode (7 cm) and predict the I_{corr} more accurately.

5. Conclusions

1. In aged Structures (dry concrete) measurement of E_{corr} and resistivity of concrete mislead the status of rebar embedded inside the concrete in such situations determination of I_{corr} (and hence CR) by GPT predicts it very close to the CR by weight-loss method.
2. In GPT, an anodic pulse of 100 μA with pulse duration of 10 seconds is able to discriminate the passive and active area of rebar.
3. EIST able to predicts the lowest CR of even less than 1 μm/y whereas it is not possible by GPT. But at corroded state of rebar, EIST predicts the CR 2-3 times less than that of CR by weight-loss method at 40 and 50 mm covers. But 20 times lower at 25 mm cover. At highest CR, GPT predict very close to the weight-loss method.

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