Corrosion monitoring of steel in concrete by galvanostatic pulse technique

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Abstract

Various non-destructive quantitative techniques based on electrochemical methods for measuring the corrosion rate of steel embedded in concrete have been used. The most important is the linear polarization method. In practice, this method gives lower corrosion rates of steel in concrete due to inclusion of the resistance of the concrete in the measurement. In order to eliminate the resistance of the concrete, a galvanostatic pulse method is used. In this method the current pulse is applied to the steel in concrete and the polarizing potential is sampled after the switching off the pulse. The performance of the galvanostatic pulse technique for monitoring the corrosion of steel in concrete has been assessed by comparing the corrosion rate values obtained by the weight loss method and linear polarization resistance method for steel reinforced in M15, M20, M30 and M35 grade concrete containing 0–5% NaCl. It is found that the galvanostatic pulse technique is able to give reliable corrosion rate values of steel in concrete.
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1. Introduction

The corrosion of the steel rebars is the main cause of damage and early failure of reinforced concrete structures. Steel embedded in good quality concrete is protected by the high alkalinity of pore water which, in the presence of oxygen, passivates the steel. The loss of alkalinity due to carbonation of the concrete and the penetration of chloride ions to steel can destroy the passive film [1–4]. The prevention and detection of deterioration of concrete infrastructures is one of the greatest challenges. Various non-destructive quantitative techniques based on electrochemical methods for measuring the corrosion rate have been used to detect the corrosion at an early stage, in order to predict residual lives and accordingly decide what preventive or repair systems are to be applied [5].

A characteristic feature of the corrosion of steel in concrete is the development of macrocells because of the coexistence of passive and corroding areas on the same rebar with a short circuited galvanic current and a open-circuit voltage of about 600 mV. This leads to an electric field with a continuous change of electrode potential from anode to cathode. This potential distribution can be measured at concrete surface using separate half cells [6–12]. Practically, the reference electrode is put on the concrete surface with wetted cotton at its tip and with the help of a high impedance voltmeter, the potentials were measured. This requires the prior removal of some portion of concrete so as to make electrical contact with the reinforcing steel, if the connections are not readily available. As one can not measure the potential over the steel surface, thus measured potential is a mixed potential. These potential values can be interpreted in a way that more negative values suggest higher probability of corrosion [13]. This concept of using open circuit potentials for interpreting corrosion of reinforcing steel embedded in a concrete sometimes lead to misleading conclusions because of the

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influence of cover depth [14], its high resistivity and limited oxygen access [15].

An acoustic method can successfully be applied to the cases where the cracks have initiated internally without any visible indications at the surface. A crude form of doing this is by sensibly hearing the characteristic hollow sound by simply striking the surface with a hammer. Because of the corrosion of steel rebars, volume of rod increases due to the existence of corrosion products. This increase in volume leads to crack initiation. Existence of an internal crack can be judged by striking the surface with a hammer and distinguishing the hollow sound from that of a crack free concrete surface. Although this method seems to be rather primitive, this is quite often used successfully. A more sophisticated form of doing this procedure with the help of piezo electric transducers and advanced electronic system for the analysis is also available now a days [16,17]. This requires more practical experience and interpreting capacity.

Even these acoustic techniques cannot be successfully used immediately just after the attack of the passive layer by aggressive ions and initiation of corrosion. As the anodic and cathodic areas are locally separated, electrochemical transport processes lead to the rust formation not directly at the anodic sites. The corrosion products are generated at sites where Fe^{2+} ions and OH^- ions meet and the dissolving capacity of the iron hydroxide is exceeded. Hence it takes some time for visual indications on the surface by the way of rust staining.

Electrochemical noise measurements [18] used for predicting the localized corrosion phenomenon at laboratory has been extended to predict the corrosion rate of steel rebar embedded in concrete [19,20] and a reasonable correlation of potential noise vs corrosion rate has been obtained.

Electrochemical linear polarization resistance (LPR) and AC impedance methods have been used to monitor the corrosion of steel in concrete for a number of decades [21–24]. Gonzalez et al. [25,26] reviewed the limitations imposed by such LPR measurements for steel in concrete.

Glass et al. [27] have studied the sensitivity of time constants of potential-time constant on application of galvanostatic pulse to the reinforced steel in concrete. Suitable model has been assigned which accurately fitted the transient data of actively corroding steel in concrete. Gonzalez et al. [28] have studied the relation between the time constant of potential transients with corrosion rate, the effect of magnitude of applied perturbing signal on corrosion rate measurement and the effect of non-uniformity of the potential distribution over the reinforcement surface. Birbilis et al. [29] have proposed a circuit model for analyzing the transient response of steel in concrete. Newton and Sykes [30] have examined the galvanostatic pulse technique as an alternative method of impedance analysis for steel corrosion in mortar under immersed condition.

These earlier studies have been dealing with analyzing the potential transient for calculation of R_p values. The time constant involved in exponential decay has been utilized for estimating the polarization resistance (R_p) values by assuming a suitable value for the interfacial double layer capacitance. Assumption of suitable double layer capacitance value for quantification purposes poses low reliability. Hence a different methodology for deriving the quantified data on corrosion rate without any such assumption is very much needed. In this paper, the performance of the device developed based on galvanostatic pulse method which can measure the polarized potential with and without IR drop of the concrete is assessed for measuring the corrosion rate of steel in concrete.

2. Principle

In general, the galvanostatic pulse method is characterized by impressing a small amplitude, short interval anodic current pulse, applied galvanostatically with the help of an external counter electrode over the concrete surface and analyzing the resultant change in potential of the steel reinforcement.

The potential transient for a given current step of ΔI to a typical Randles circuit under galvanostatic condition is given by

$$\eta_t = \Delta I R_c + \Delta I R_p (1 - \exp(-t/C R_p)) \tag{1}$$

where η_t is the total change in the potential of the test electrode, $\Delta I R_c$ is the ohmic drop in the concrete, R_p and C are the polarization resistance and electrical double layer capacitance of the corroding interface. Upon the interruption of the current pulse, the ohmic drop contribution $\Delta I R_c$ is immediately lost by the electrode potential and a sudden fall of potential to a value within few microseconds gives the actual polarization of the test specimen. In the absence of any further current, the potential decays exponentially with time according to

$$\eta_t / \eta_{max} = \exp(-t/C R_p) \tag{2}$$

where η_{max} is the maximum polarization at the time of current interruption and η_t is the polarization at any instant of time.

Typical schematic potential transient for a current pulse under galvanostatic condition is shown in Fig. 1 where an anodic current pulse (Fig. 1(a)) of amplitude Δi is impressed between the time $t = t_0$ to $t = t_1$. Upon applying the current pulse, the potential of the system shifts to a value equivalent to $\Delta I R_c$ in few microseconds and thereafter increases gradually to a maximum value η_{max}. At the instant of time $t = t_1$ when the current pulse is switched off, the potential value drops suddenly to a value equivalent to $\Delta I R_c$ (IR drop) and starts decaying exponentially. As the passive steel can easily be polarized, non-corroding reinforcement rod shows much higher potential difference (Fig. 1(b)) than that of a corroding (Fig. 1(c)).
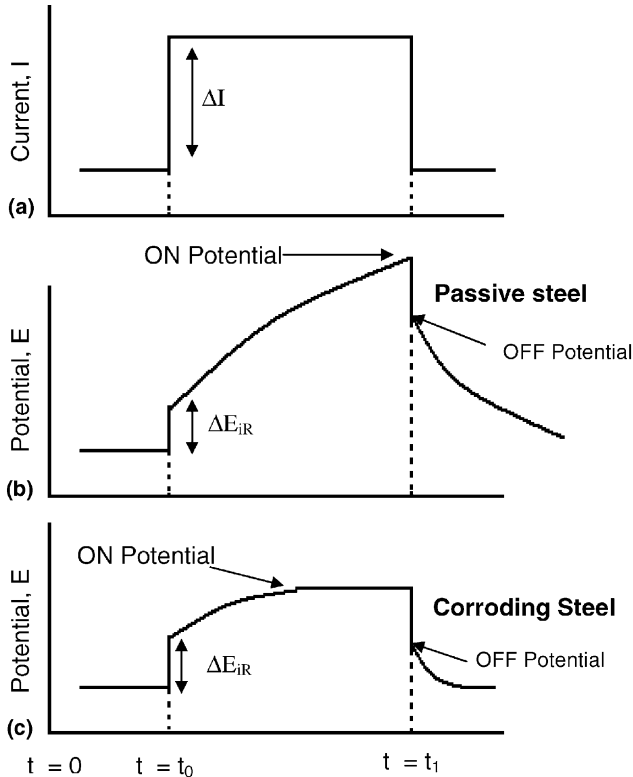
Fig. 1. Nature of potential transient of steel in concrete for a galvanostatic current pulse: (a) current input, (b) potential transient for passive steel, (c) potential transient for corroding steel.

3. Materials and methods

A portable device based on galvanostatic pulse technique to measure the polarized potential after eliminating the IR drop has been assembled. Fig. 2 shows the block diagram of the instrument [31]. This unit has the facility to operate at two different current settings of 100 μA and 300 μA. A monostable multivibrator generates a pulse width of 60 s. Such a pulse was impressed to the reinforcing steel with the help of a specially designed probe. One branch of the remaining circuitry senses the positive slope of the resultant potential transient and samples and hold the potential value at the instant of 60th second from the start of the pulse. This polarizing potential is designated as ON potential. The other branch which includes the IR drop of concrete of the circuitry senses the negative slope of the potential transient, i.e. after the 60th second, and samples and hold the potential at the instant of 100 μs after the cut off of the current pulse. This potential is designated as OFF potential which is free from IR drop value of concrete. These ON and OFF potentials were sampled at appropriate times and hold in the memory by the sample and hold circuitry (S/H) which can be read from the digital panel meter (DPM).

A special probe is made of PVC with a wetted sponge which holds a piece of stainless steel (counter electrode, 1 cm × 5 cm) and a saturated calomel electrode. The counter electrode and reference electrode was fixed permanently to the PVC block with wetted sponge making electrical circuitry. The schematic diagram of special probe is shown in Fig. 3. This probe, along with the connection with the reinforcing steel (working electrode), completes the conventional three electrode assembly and was used for both LPR and galvanostatic pulse measurements. This hand held probe gives reproducible results even the applied pressure varies resulting in compression of sponge. The photograph of the instrument with probe and concrete cube is shown in Fig. 4.
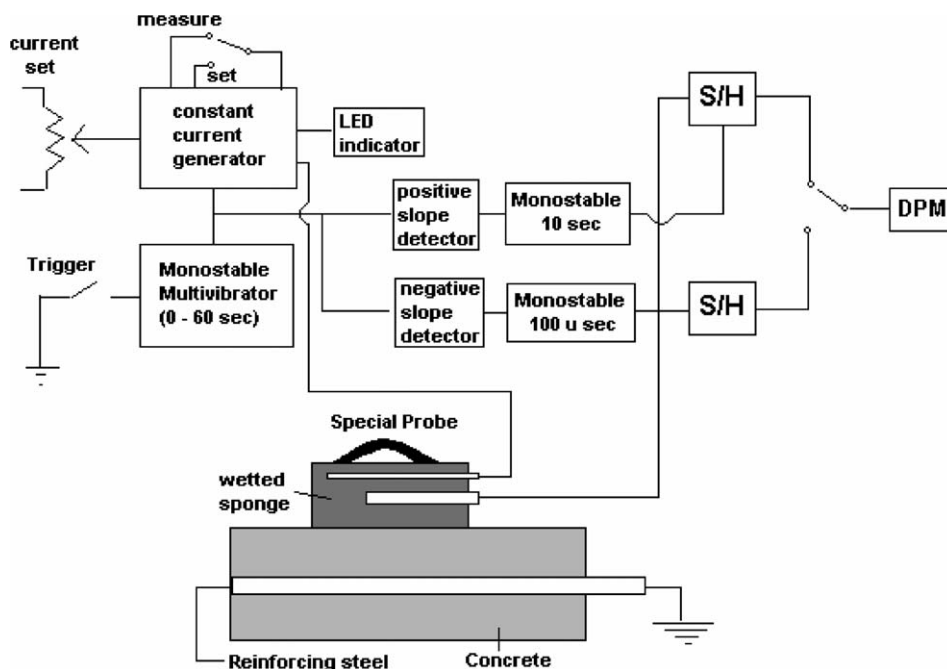

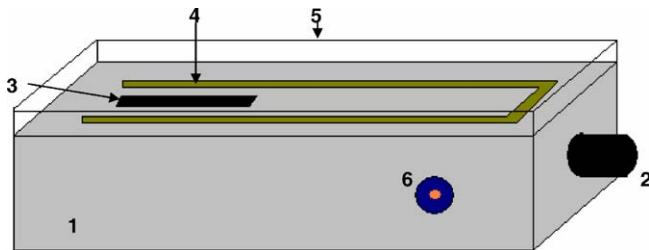Fig. 2. Block diagram of the galvanostatic pulse circuitry.

Fig. 3. Schematic diagram of special probe: (1) PVC; (2) reference electrode; (3) hole for wetted sponge; (4) SS counter electrode; (5) wetted sponge; (6) electrical connection for counter electrode.

Table 1
Details of concrete mix proportions

Concrete grade	Average compressive strength (MPa)	Mix proportions			
		Cement	Fine aggregate	Course aggregate	W/C ratio
M15	15	1	1.56	2.24	0.50
M20	20	1	1.71	2.09	0.50
M30	30	1	1.14	1.86	0.38
M35	35	1	1.14	1.86	0.35

The main advantage of this instrument is that the measurement is made in just 60 s and the possibility of holding the polarized potential free from IR drop of concrete which will be highly useful for on-site measurements.

The performance of this instrument has been evaluated for concrete cubes of strengths M15, M20, M30 and M35 containing 0%, 1%, 3% and 5% chloride ion concentrations by weight of cement. Details about the concrete mix proportions are given in Table 1. Local clean river sand (fineness modulus of medium sand equal to 2.6) conforming to grading zone III of IS-383-197 was used as fine aggregate and locally available aggregates conforming to graded aggregates of normal size greater than 4.75 mm and less than 10 mm of IS-456-2000 was used as coarse aggregate. Chlorides were added to the concrete during the casting of the specimen. The concrete cubes were of $100 \times 100 \times 100$ mm size with an embedded steel rod of diameter 5 mm exposing a length of 50 mm. 25 mm cover thickness was provided to the reinforcement bar. The schematic diagram of concrete cube with reinforcement bar is shown in Fig. 5. These reinforced concrete specimens were cured for 28 days in distilled water. After the curing period was over, a 10 mm thick mortar bund was constructed along the edges of the cubes using 1:1 cement mortar and the joints between the concrete and the mortar were perfectly sealed with epoxy to prevent any leakage. Then these specimens were alternatively wetted with chloride free distilled water once in a day and kept dry for the remaining period for a period of about 6 years. The wet cycle was for a per-
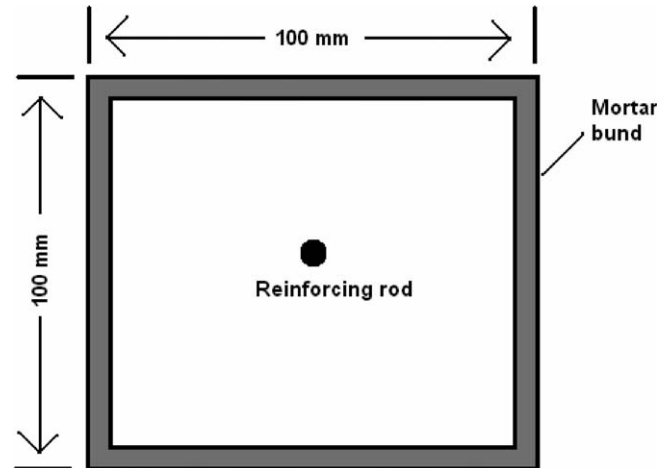

Fig. 5. Schematic diagram of concrete cube.

iod of 8 h and the dry cycle was for a period of 16 h. The corrosion rates of the embedded steel rods were also obtained by gravimetric method by measuring the weight loss of the 50 mm length and 5 mm diam rod embedded in concrete near to that of the rod used for electrochemical studies. These rods made out of the same material of that of reinforcing rod, were polished mechanically to mirror finish before casting and the initial weight was measured. After the test period was over, the concrete cubes were broken open and the weight loss samples were removed and cleaned thoroughly without any residual concrete over it and final weight was measured. From the mass loss values,

Fig. 4. Photograph of the galvanostatic pulse instrument with probe and concrete sample.

the corrosion rate in millimeter per year (mmpy) was obtained by using the following relationship,

$$\text{Corrosion rate (mmpy)} = \frac{87.6 \times \text{mass loss (mg)}}{\text{Area (cm}^2) \times \text{Time (h)} \times \text{Density}} \tag{3}$$

Linear polarization resistance measurements were also carried out for steel rod in different concrete strengths as that of galvanostatic pulse technique by polarizing the electrode from −20 mV to +20 mV with respect to open circuit potential (OCP) using Electrochemical System (1280 B Solartron, UK). No data could be acquired with IR eliminated LPR with the instrument. The corrosion rates were obtained by using the relationship,

$$i_{\text{corr}} = \frac{B}{R_p} \tag{4}$$

where B was 0.026 V for corroding and 0.052 V for non-corroding steel in concrete [32]. From the measured i_{corr} values, the corrosion rates in mmpy were obtained from the relationship,

$$\text{C.R. (mmpy)} = 0.012 \times i_{\text{corr}} \ (\mu A/cm^2) \tag{5}$$

To avoid over polarization of reinforcing rods, the LPR measurement was made first and then the galvanostatic pulse measurement was made. Even while doing the galvanostatic pulse measurements, the current was impressed for 1 min only. After the measurement of ON and OFF potential for individual measurements, it is found that the OCP restores to the original un polarized values immediately confirming that the galvanostatic pulse method is a non-destructive method. Also, the circuitry has the facility to sample and hold the ON and OFF potentials which one can record after the current pulse was impressed, no trace of the transient is obtained.

4. Results and discussion

4.1. Qualitative estimation of corrosion

The open circuit potentials, the polarized potentials with IR drop (ON potential) and polarized potentials without IR drop (OFF potentials) measured for concrete cubes of strength M15, M20, M30, M35 having various percentages of chloride in it are shown in Figs. 6–9, respectively. It can be seen from these figures that the polarized potentials (both ON and OFF potentials) are very large, greater than 500 mV compared to their open circuit potential in case of concrete cubes made with 0% chloride and these values decrease gradually and become close to the respective open circuit potentials in the case of concrete cubes containing more chloride ions. This result can be interpreted as concrete cube containing 0% chloride has reinforcing steel in good condition with out corrosion (passive state) and shows larger polarizations while with increase in concentra-
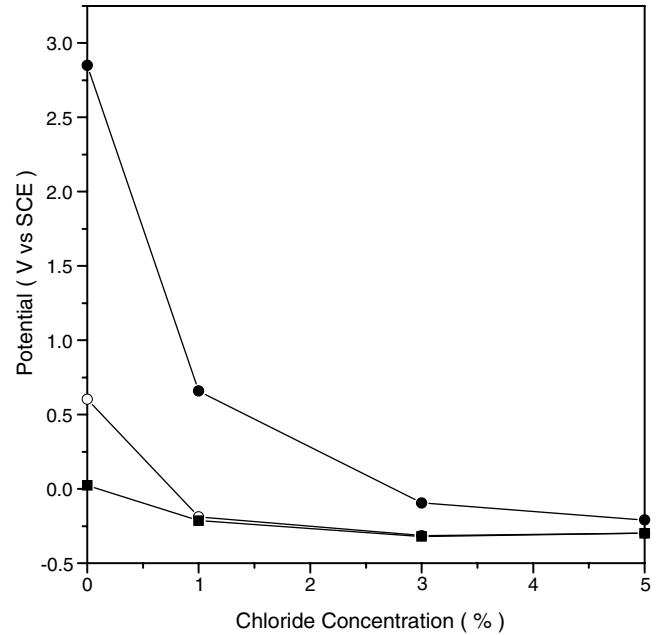

Fig. 6. Potential values for steel in M15 grade concrete in the presence of chloride: (●) ON potential; (○) OFF potential; (■) open circuit potential.
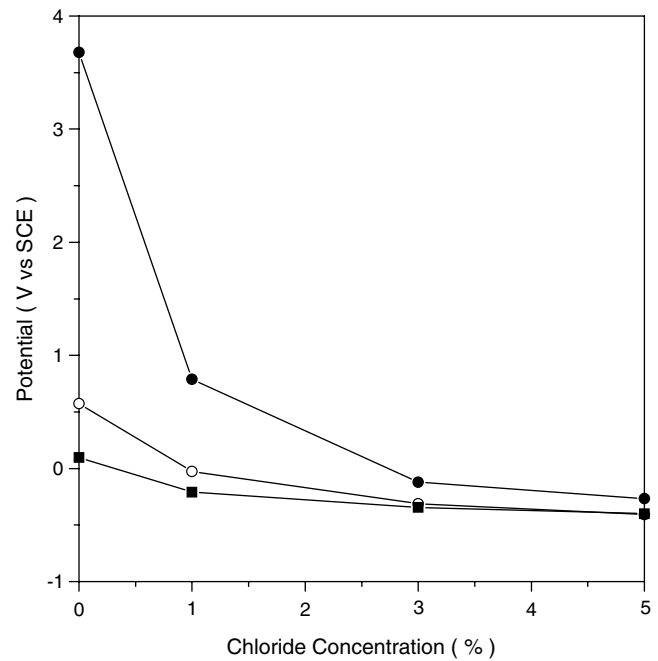

Fig. 7. Potential values for steel in M20 grade concrete in the presence of chloride: (●) ON potential; (○) OFF potential; (■) open circuit potential.

tion of added chloride to the concrete mixture, over the period, the corrosion might have established and the corroded reinforcing steel rod in a concrete shows less or negligible polarization. Also, the difference between the ON and OFF potential is very high in the case of passive steel in concrete and this difference decreases and approaches the value of open circuit potential with increasing chloride concentrations i.e. in the case of corroding steel in concrete.
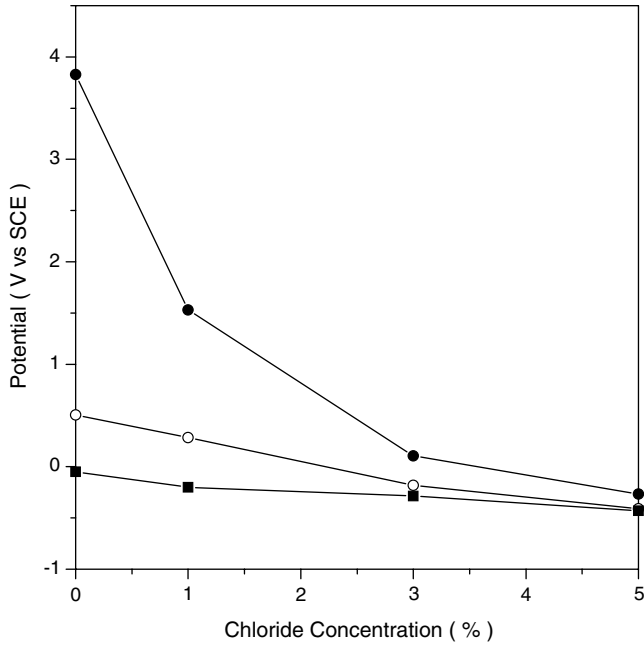
Fig. 8. Potential values for steel in M30 grade concrete in the presence of chloride: (●) ON potential; (○) OFF potential; (■) open circuit potential.
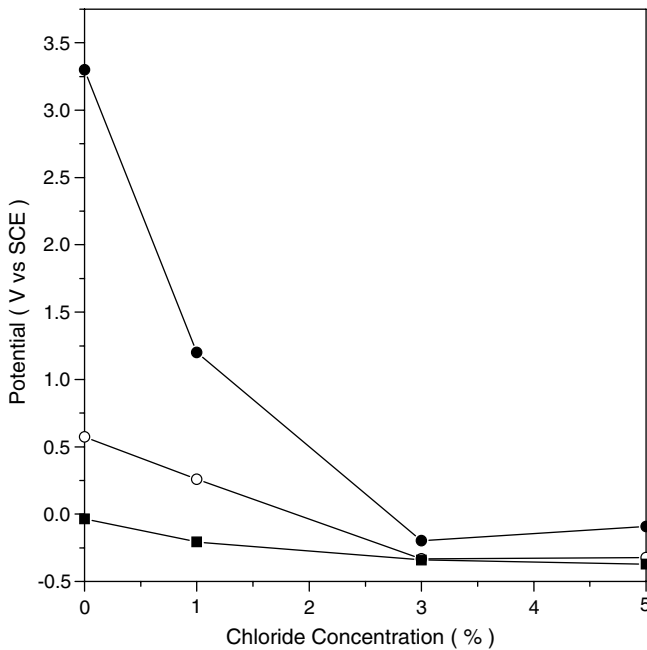

Fig. 9. Potential value of steel in M35 grade concrete in the presence of chloride: (●) ON potential; (○) OFF potential; (■) open circuit potential.

In order to evaluate the efficacy of the developed instrument, measurements of potentials of steel in concrete under immersed condition in 3% NaCl was made. Under wet conditions, where the dissolved oxygen's accessibility leads to misinterpretation of data in case of iso-potential mapping method, as shown in Table 2. For comparison, the numerical values of OCP, ON and OFF potentials of M20 concrete cubes made with chloride free, with 3% and 5% chloride are also presented. This table clearly shows that even though the open circuit potential is very negative i.e. −0.581 V for steel in concrete under fully immersed in 3% NaCl indicating the highly corroding nature of the reinforcing rod as per the potential mapping, the ON and OFF potential measured by the instrument are showing high positive values viz. +0.605 V and +0.428 V, respectively, indicating the passive state of the embedded rod. In other cases, i.e. under non-wet conditions the predictions of potential mapping and that of the measurements made with the developed instrument are in the same line. To confirm these results, the concrete cubes were broken open after the measurements and the state of the reinforcing rod in these cubes is also examined. The corrosion rate values of steel were also measured by gravimetric method (Table 1). It is very clear that the predictions of the potential mapping and galvanostatic pulse method are similar in normal cases while the measurements made with wet concrete confirms the reliability of the galvanostatic method and misleading nature of potential mapping.

4.2. Quantitative estimation of corrosion

Preceding results show how the developed instrument can be used to predict qualitatively the corroded areas of a reinforcing steel in concrete. The same measurement can be used for getting quantified corrosion rate. Under high anodic polarization conditions, leading to potential shift in the tafel region, the current can be given as

$$i_a = i_{corr} \exp(2.3\eta_a/b_a) \tag{6}$$

where η_a is the overpotential, b_a is the anodic tafel slope and i_{corr} is the corrosion current.

The OFF potential is stored in the memory of the developed instrument which is the over potential (η_a) without the incorporation of ohmic drop. The b_a value of 0.07 V for steel in concrete containing chloride has been found by Tafel polarization method [33]. Using this b_a in the

Table 2
Experimental results with the developed instrument for steel in M20 concrete

Condition	OCP V vs SCE	ON potential V vs SCE	OFF potential V vs SCE	Visual observation	Corrosion rate (mmpy) [gravimetric method]
Chloride free	+0.097	+3.83	+0.575	No corrosion	Nil
+3% Chloride	−0.342	+0.106	−0.313	Moderately corroded	0.0570
+5% Chloride	−0.413	−0.265	−0.406	Fully corroded	0.080
Chloride free but with continuous immersion in 3% NaCl for 18 months	−0.581	+0.605	+0.428	No corrosion	Nil

Table 3
Corrosion rates of steel in concrete obtained by galvanostatic pulse technique

Concrete grade	Chloride concentrations, %	OCP V vs SCE	OFF potential V vs SCE	Polarization η_a V vs SCE	Corrosion rate (mmpy)
M15	0	0.024	0.603	0.579	4.375E−10
	1	−0.213	−0.189	0.024	0.036
	3	−0.321	−0.316	0.005	0.068
	5	−0.299	−0.295	0.004	0.070
M20	0	0.097	0.575	0.478	1.20E−8
	1	−0.210	−0.026	0.184	0.00001
	3	−0.342	−0.313	0.029	0.031
	5	−0.413	−0.406	0.007	0.064
M30	0	−0.049	0.505	0.554	9.95E−10
	1	−0.200	0.284	0.484	9.92E−9
	3	−0.286	−0.182	0.104	0.0026
	5	−0.431	−0.411	0.020	0.041
M35	0	−0.036	0.575	0.611	1.53E−10
	1	−0.207	0.259	0.466	1.79E−8
	3	−0.340	−0.333	0.007	0.064
	5	−0.370	−0.323	0.047	0.017

Table 4
Comparison of corrosion rates of steel in concrete obtained by galvanostatic pulse technique, linear polarization resistance method and gravimetric method

Concrete grade	Chloride concentrations, %	Corrosion rate (mmpy)		
		Galvanostatic pulse technique	Linear polarization resistance method	Gravimetric method
M15	0	4.375E−10	0.00015	Nil
	1	0.036	0.0021	0.0265
	3	0.068	0.0030	0.0875
	5	0.070	0.0010	0.082
M20	0	1.20E−8	0.0002	Nil
	1	0.00001	0.0003	Nil
	3	0.031	0.002	0.057
	5	0.064	0.0015	0.080
M30	0	9.95E−10	0.0004	Nil
	1	9.92E−9	0.0005	Nil
	3	0.0026	0.0015	0.025
	5	0.041	0.0013	0.03
M35	0	1.53E−10	0.00050	Nil
	1	1.79E−8	0.0004	Nil
	3	0.064	0.0015	0.055
	5	0.017	0.0014	0.018

above expression, i_{corr} can be computed which can be converted into corrosion rate in mmpy using the relationship (Eq. (5)).

The results of the corrosion rates for the reinforcing steel in various strengths of concrete having chloride ion concentrations of 0–5% are presented in Table 3. These concrete cubes were broken open after the experiment and the corrosion rates were also evaluated using the conventional weight loss method. Besides, the corrosion rate values were also obtained from linear polarization resistance method. Table 4 compares the corrosion rate values of steel in concrete obtained by galvanostatic pulse technique, gravimetric method and LPR method. The corrosion rate values of steel in concrete are found to be dependent on the strength as well as the percentage of chloride present in the concrete. On increasing the strength from M15 to M35, the corrosion rates are decreased for a given chloride concentrations. Further it has been found that the corrosion rates obtained by the galvanostatic pulse method using the developed instrument and weight loss method agree well in most of the studied system. However, the corrosion rate values obtained by the LPR method are found to be one order lower than that of the actual corrosion rates for steel in concrete in the presence of chloride due to the inclusion of resistance of the concrete in the measured R_p values.

5. Conclusions

The device developed based on the anodic galvanostatic pulse technique is found to give more reliable results about the state of reinforcing steel in concrete and the rate of corrosion. The corrosion rates obtained by LPR method has been found to give lower values than that of actual corrosion rates due to inclusion of resistance of concrete in the LPR measurements.

Acknowledgements

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