Corrosion Monitoring of Reinforced Concrete Structures - A Review

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Reinforced concrete structures have the potential to be very durable and capable of withstanding a variety of adverse environmental conditions. However, failures in the structures do still occur as a result of premature reinforcement corrosion. The maintenance and repair of bridges and buildings for their safety requires effective inspection and monitoring techniques for assessing the reinforcement corrosion. Engineers need better techniques for assessing the condition of the structure when the maintenance or repair is required. These methods need to be able to identify any possible durability problems within structures before they become serious. This paper reviews all the electrochemical and nondestructive techniques from the point of view of corrosion assessment and their applications to bridges, buildings and other civil engineering structures.

1. INTRODUCTION

Corrosion of reinforcement has been established as the predominant factor causing widespread premature deterioration of concrete construction worldwide, especially of the structures located in the coastal marine environment [1]. The most important causes of corrosion initiation of reinforcing steel are the ingress of chloride ions and carbon dioxide to the steel surface. After initiation of the corrosion process, the corrosion products (iron oxides and hydroxides) are usually deposited in the restricted space in the concrete around the steel. Their formation within this restricted space sets up expansive stresses, which crack and spall the concrete cover. This in turn results in progressive deterioration of the concrete. As a result, the repair costs nowadays constitute a major part of the current spending on

infrastructure. Quality control, maintenance and planning for the restoration of these structures need non-destructive inspections and monitoring techniques that detect the corrosion at an early stage. Corrosion loss consumes considerable portion of the budget of the country by way of either restoration measures or reconstruction. There have been a large number of investigations on the problems of deterioration of concrete and the consequent corrosion of steel in concrete. Properly monitoring the structures for corrosion performance and taking suitable measures at the appropriate time could effect enormous saving. Moreover, the repair operation themselves are quite complex and require special treatments of the cracked zone, and in most instances the life expectancy of the repair is limited. Accordingly, corrosion monitoring can give more complete information of changing condition of a structure in time [2-5].

Many of the strategic reinforced and prestressed concrete structures have started showing signs of distress with in a short period usually the condition of the structures is monitored by visual inspection and remedial measures are resorted to only when the condition becomes very serious by way to heavy rusting of steel reinforcements followed by cracking and spalling on concrete. It is desirable to, monitor the condition of such strategic structures right from the construction stage by carrying out periodic corrosion surveys and maintaining a record of data. For measurement of the corrosion rate of reinforcing steel in concrete, many electrochemical and non-destructive techniques are available for monitoring corrosion of steel in concrete structures. Rebar corrosion on existing structures can be assessed by different methods such as:

1. Open circuit potential (OCP) measurements
2. Surface potential (SP) measurements
3. Concrete resistivity measurement
4. Linear polarization resistance (LPR) measurement
5. Tafel extrapolation
6. Galvanostatic pulse transient method
7. Electrochemical impedance spectroscopy (EIS)
8. Harmonic analysis
9. Noise Analysis
10. Embeddable corrosion monitoring sensor and
11. Cover thickness measurements
12. Ultrasonic pulse velocity technique
13. X-ray, Gamma radiography measurement
14. Infrared thermograph Electrochemical
15. Visual inspection

1.1.   Open Circuit Potential (OCP) Measurements

The tendency of any metal to react with an environment is indicated by the potential it develops in contact with the environment. In reinforced concrete structures, concrete acts, as an electrolyte and the

reinforcement will develop a potential depending on the concrete environment, which may vary from place to place. The schematic diagram for open circuit potential measurements is as shown in Fig.1
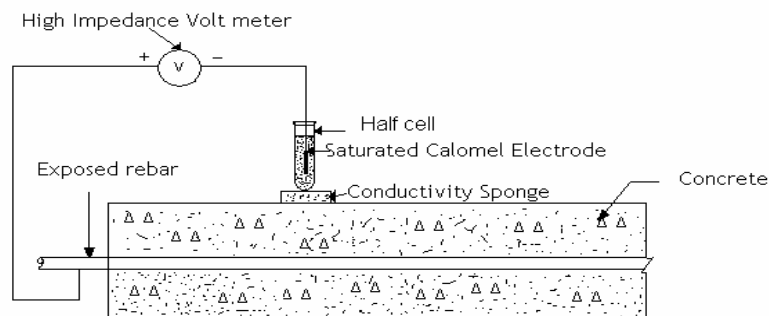

Figure 1. Schematic representation of Open circuit potential (OCP) measurement

The principle involved in this technique is essentially measurement of corrosion potential of rebar with respect to a standard reference electrode, such as saturated calomel electrode (SCE), copper/copper sulfate electrode (CSE), silver/ silver chloride electrode etc. As per ASTM C 876 [6] standards, the probability of reinforcement corrosion is as follows in Table 1.

Table 1. Corrosion condition related with half-cell potential (HCP) measurements [6]

Open circuit potential (OCP) values		Corrosion condition
(mV vs. SCE)	mV vs. CSE	
< -426	< -500	Severe corrosion
< -276	< -350	High (<90% risk of corrosion)
-126 to -275	-350 to -200	Intermediate corrosion risk
> -125	> -200	Low(10% risk of corrosion)

The detection and measurement of corrosion in concrete structures are essential. Although there are several methods for the diagnosis, detection and measurement of corrosion in reinforcing steel, there is no consensus regarding which method assesses corrosion levels in reinforced concrete structures most accurately. Various techniques for detecting and measuring corrosion will provide data on the causes, detection or rate of corrosion [7]. The main method of detection of corrosion is the half-cell potential (HCP) measurements. The corrosion process of steel in concrete can be followed using several electrochemical techniques. Monitoring of open circuit potential (OCP) is the most typical procedure to the routine inspection of reinforced concrete structures [8-10]. Its use and interpretation are described in the ASTM C876 *Standard Test Method for Half-Cell Potential of Reinforcing Steel in Concrete* [6]. Potential readings, however, are not sufficient as criterion, since they are affected by a number of factors, which include polarization by limited diffusion of oxygen [11, 12], concrete

porosity [13] and the presence of highly resistive layers [13]. According to this method if the potential of steel in concrete becomes more negative than -276mV vs. SCE there is a 90% probability that corrosion will occur. It is a non-destructive test that collects an enormous quantity of data from a large structural area. Establishing structures potential map, according to ASTM C876-91, is the most commonly applied electrochemical technique for diagnosing the corrosion risk of reinforced concrete structures [14,15]. However it is generally accepted that corrosion potential measurements must be complemented by other methods [15], because although reliable relationships between potential and corrosion rate can be found in the laboratory for well established conditions [16,17], these can in no way be generalized, since wide variations in the corrosion rate are possibly in very narrow range of potentials [18]. Open circuit potential measurement is a useful technique in finding out the anodic and cathodic sites in reinforced concrete structures provided the reinforcing bars are exposed to the environments. Many authors have studied the effectiveness of the test and got useful results [19-23]. OCP values only can provide information for corrosion probability and cannot indicate the rate of corrosion [24].

1.2   Surface Potential (SP) Measurements

During corrosion process, an electric current flow between the cathodic and anodic sites through the concrete and this flow can be detected by measurement of potential drop in the concrete. Hence surface potential measurement is used as a non-destructive testing for identifying anodic and cathodic regions in concrete structure and indirectly detecting the probability of corrosion of rebar in concrete. Two reference electrodes are used for surface potential measurements as shown in Fig.2. No electrical connection to the rebar is necessary in this technique. In this measurement, one electrode is kept fixed on the structure on a symmetrical point. The other electrode called moving electrode is moved along the structure on the nodal points of the grid as mentioned in OCP measurements. The potential of movable electrode, when palced at nodal points, is measured against the fixed electrode using a high impedance voltmeter. A more positive potential reading represents anodic area where corrosion is possible. The greater the potential difference between anodic and cathodic areas greater is the probability of corrosion.
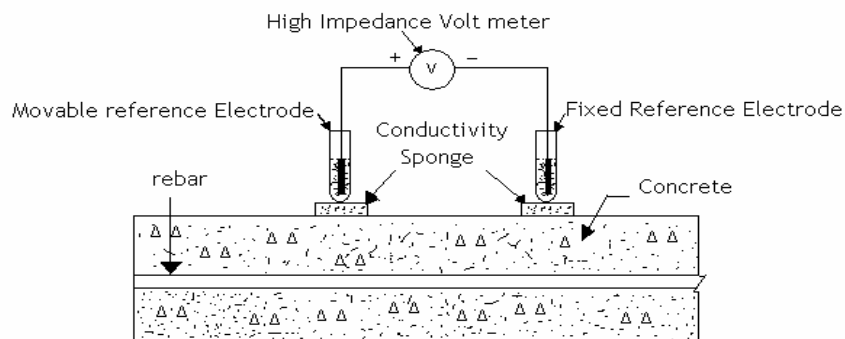

Figure 2. Schematic representation of surface potential (SP) measurements

This is another useful non-destructive technique to know the condition of steel rebar embedded inside the concrete. Various condition survey assessments have been made using this technique [25].

1.3. Concrete Resistivity Measurement

The electrical resistivity of concrete is an important parameter concerning determination of intensity of the initiated corrosion process. In concrete material with high electrical resistivity the corrosion process will be slow compared to concrete with low resistivity in which the current can easily pass between anode and cathode areas. Two different techniques, namely AC and DC measurements are used for determination of electrical resistivity. In these measurements both surface and embedded probes are applied. Applying a constant electric field between the two embedded electrodes and measuring the resulting current as a voltage drop over a small resistance accomplish the DC measurements. The AC measurements can be conducted both by means of two and four-pin methods. The most common surface mounted probe is known as the Wenner array. An alternating current is passed between the outer electrodes and the potential between the inner electrodes is measured. Concrete resistivity is generally measured by using the Wenner four probe method as shown in Fig.3.
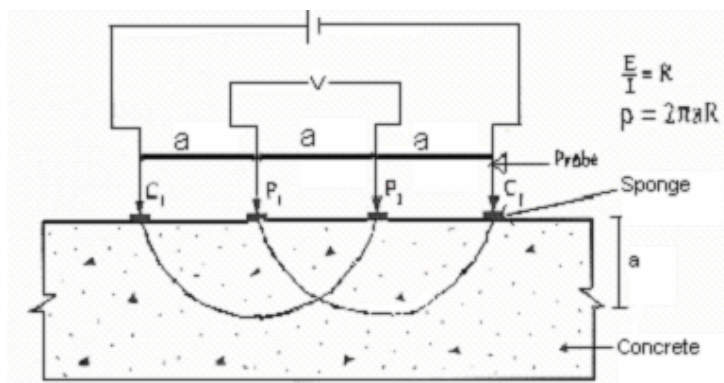

Figure 3. Circuit for electrical resitance measurements

A known current `I' is impressed on the outer probes and the resulting potential drop `V' between the inner probes is measured and resistance `R' is given by V/I.
Resistivity of concrete (ρ) = $2\Pi aR$
　　　Where a is the inner electrode distance in cm
　　　 R is the measured resistance in ohm.
Generally, the electrical resistivity of concrete can be measured with good reproducibility using different techniques for specimens in various shapes and sizes on the assumption that the applied electrodes are well bound to the concrete and the spacing between them is adjusted to the dimensions of test sample. The electrical resistivity of concrete is being increasingly used indirectly to evaluate concrete characteristics such as the chloride ion diffusivity, the degree of concrete saturation and its aggressiveness [26,27]. This parameter may also provide useful information regarding the rebar

corrosion performance in concrete [28]. As indicated by Feliu and coworkers [29], the electrical resistivity of concrete is inversely proportional to the corrosion rate. This observation was supported by Glass et al. [30], who showed that the effect of mortar resistivity on the rebar corrosion rate was strongly dependent on the environmental relative humidity. Lopez and Gonzalez [31] have shown that the concrete pores saturation level governs the resistivity and the corrosion rate. Even when the influence of concrete resistivity on the rebar corrosion rate is evident, there are important differences in the threshold values of ρ proposed by several authors in order to evaluate the degree of rebar corrosion [32-34].

It was reported that the electrical resistivity of concrete was proposed as an effective parameter to evaluate the risk of reinforcing steel corrosion, particularly when corrosion is induced by chloride attack [35]. The resistivity of concrete is strongly dependent on the concrete quality and on the exposure conditions, such as the relative humidity and also temperature affects the degree of concrete pore saturation [36,37] and so the resistivity values.

A number of authors [34,38] have related corrosion and resistivity as follows in Table 2.

Table 2. Corrosion risk from resistivity

Resistivity (Ohm.cm.)	Corrosion risk
Greater than 20,000	Negligible
10,000 to 20,000	Low
5,000 to 10,000	High
Less than 5,000	Very high

Clear [39] measured resistances between upper and lower reinforcing mats in slabs stored in an outdoor exposure conditions and found that there was a significant current flow observed at resistivity in excess of 20,000 ohm.cm. Tremper et al. [40] investigated a structure in a marine environment and state that a resistivity of 60,000 ohm.cm is required to inhibit or prevent corrosion.

Concrete resistivity influences the effectiveness and durability of cathodic protection (CP) of concrete structures [41-43]. Similarly it is important for electrochemical chloride removal and realkalisation [44]. For a large variation in resistivity within a structure it is more difficult to obtain uniform protection (CP) or a well-predicted result (chloride removal, realkalisation).

The resistivity measurement is a useful additional measurement to aid in identifying problem areas or confirming concerns about poor quality concrete. Measurements can only be considered along side other measurements. Reinforcing bars will interfere with resistivity measurements.

1.4   Linear Polarization Resistance Measurement (LPR)

The LPR technique has become a well-established method of determining the instantaneous corrosion rate measurement of reinforcing steel in concrete [45-48]. The technique is rapid and non-intrusive, requiring only localized damage to the concrete cover to enable an electrical connection to be made to

the reinforcing steel. Due to the widespread corrosion of reinforcing steel in concrete structures there has been a concerted demand for the development of non-destructive techniques to enable accurate assessment of the condition of reinforced concrete structures. LPR monitoring has been developed to address this need. The technique is rapid and non-intrusive, requiring only a connection to the reinforcing steel. The data provides a valuable insight into the instantaneous corrosion rate of the steel reinforcement, giving more detailed information than a simple potential survey. The LPR data enables a more detailed assessment of the structural condition and is a major tool in deciding upon the optimum remedial strategy to be adopted. It is thus imperative that the LPR measurements obtained are accurate.

In LPR measurements the reinforcing steel is perturbed by a small amount from its equilibrium potential. This can be accomplished potentiostatically by changing the potential of the reinforcing steel by a fixed amount, ΔE, and monitoring the current decay, ΔI, after a fixed time. Alternatively it can be done galvanostatically by applying a small fixed current, ΔI, to the reinforcing steel and monitoring the potential change, ΔE, after a fixed time period. In each case the conditions are selected such that the change in potential, ΔE, falls within the linear Stern–Geary range of 10–30 mV [49]. The polarization resistance, R_p, of the steel is then calculated from the equation

$$R_p = \Delta E / \Delta I \tag{1}$$

From which the corrosion rate, I_{corr}, can then be calculated

$$I_{corr} = B / R_p \tag{2}$$

where, B is the Stern–Geary constant. A value of 25 mV has been adopted for active steel and 50 mV for passive steel [50]. In order to determine the corrosion current density, i_{corr}, the surface area, A, of steel that has been polarized needs to be accurately known:

$$i_{corr} = I_{corr} / A \tag{3}$$

The present residual strength and, by extrapolation, the remaining service life of the structure can then be estimated. In a conventional LPR test the perturbation is applied from an auxiliary electrode on the concrete surface (Fig.4). The surface area of steel assumed to be polarized is that lying directly beneath the auxiliary electrode. However, there is considerable evidence to suggest that the current flowing from the auxiliary electrode is unconfined and can spread laterally over an unknown, larger area of steel [51, 52]. This can lead to inaccurate knowledge of the surface area of steel polarized and result in an error in the calculation of the corrosion current density, which, in turn, will produce an inaccurate estimate of the condition of the structure being investigated.

In order to overcome the problem of confining the current to a predetermined area, the use of a second auxiliary guard ring electrode surrounding the inner auxiliary electrode has been developed [53-58]. The principle of this device is that the outer guard ring electrode maintains a confinement current during the LPR measurement. This confinement current prevents the perturbation current from

the main inner auxiliary electrode spreading beyond a known area. In order to select an appropriate level for the confinement current two sensor electrodes are placed between the inner and outer auxiliary electrodes. The potential difference between these sensor electrodes is monitored and a confinement current selected to maintain this potential difference throughout the LPR measurement [59]. Fig.5 shows the set-up of guard ring technique.
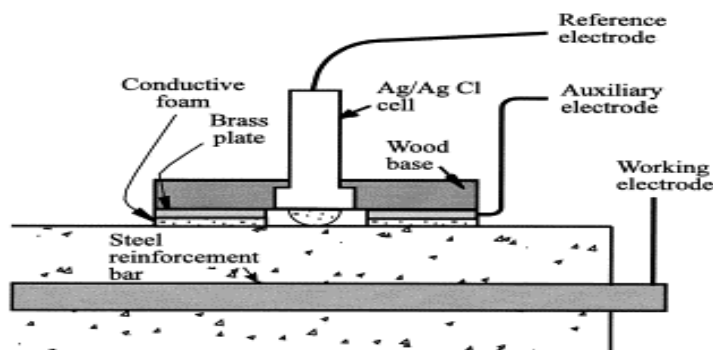

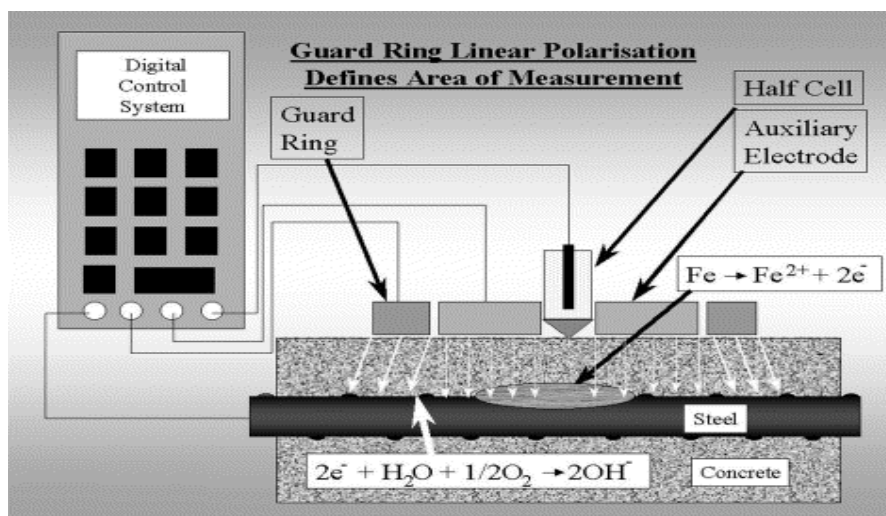**Figure 4.** Linear polarization resistance measurement

Figure 5. Guard ring test set-up

The performance of the guard ring has been shown to be an improvement upon that of a single unconfined auxiliary electrode, giving a more accurate value for the corrosion rate of the reinforcing steel being monitored. At present the established method of guard ring LPR measurements uses galvanostatic control. This method relies upon the potential response, ΔE, to the selected perturbation, ΔI, falling within the linear region of the Stern–Geary plot. The use of a potentiostatic device would enable the potential shift itself to be selected, ensuring the measurement falls within this linear region and hence, would not risk the inaccuracies incurred by applying too large a galvanostatic perturbation.

It is the most advanced of those developed so far and in many cases it can successfully confine the polarization area. However, in some cases, e.g., when the cover concrete is too thick, the confinement of the polarization area may not be achieved. Flis et al. [14] used numerical technique to determine the influences of various parameters, including the cover thickness, on the current distribution in reinforced concrete. They concluded that the polarization area increased significantly with increasing cover thickness.

Fig.6 shows the embeddable linear polarization sensor used for new construction. The measurement can be made with an embedded half-cell against a mild steel "working electrode" with one or more stainless steel auxiliary electrodes. The mild steel working electrode should be fully representative of the actual reinforcement and should accurately represent the corrosion rate of the steel around it, if embedded at the same cover and suitable consolidation occurs. There may be slight differences due to differences in the steel surface between ribbed slightly corroded bars and a smooth electrode, and macro cell effects may be different if the electrode is left unconnected to the steel between readings.
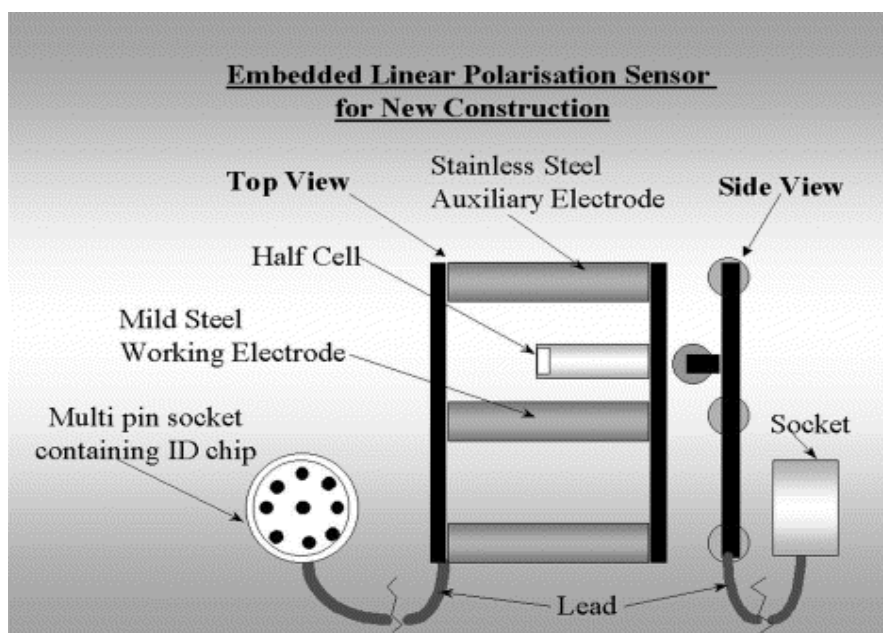

Figure 6. Embedded linear polarization sensor for new construction

The following broad criteria for corrosion have been developed from field and laboratory investigations with the sensor controlled guard ring device [60] given in Table 3.

These measurements are affected by temperature and humidity, so the conditions at the time of measurement affect the interpretation of the limits defined above. The measurements should be considered accurate to within a factor of two. Work has been done in correlating I_{corr} to section loss and end of service [61].

Table 3. Corrosion current vs. condition of the rebar [60]

Corrosion current (I_{corr})	Condition of the rebar
$I_{corr} < 0.1 \ \mu A/cm^2$	Passive condition
$I_{corr} \ 0.1 - 0.5 \ \mu A/cm^2$	Low to moderate corrosion
$I_{corr} \ 0.5 - 1.0 \ \mu A/cm^2$	Moderate to high corrosion
$I_{corr} > 1.0 \ \mu A/cm^2$	High corrosion rate
The device without sensor control has the following recommended interpretation.	
$I_{corr} < 0.2 \ \mu A/cm^2$	No corrosion expected
$I_{corr} \ 0.2 - 1.0 \ \mu A/cm^2$	Corrosion possible in 10 -15years
$I_{corr} \ 1.0 - 10 \ \mu A/cm^2$	Corrosion expected in 2-10years
$I_{corr} > 10 \ \mu A/cm^2$	Corrosion expected in 2 years or less

1.5   Tafel Extrapolation

The Tafel extrapolation technique (TP) is another electrochemical method for calculating corrosion rate based on the intensity of the corrosion current (I_{corr}) and the Tafel slopes. Tafel slopes also could be used to calculate corrosion rate with LPR [62-65].

Both LPR and TP techniques are based upon application of either steady fixed levels of current, followed by monitoring of the potential (galvanostatic) or application of specific potential followed by monitoring of the current (potentiostatic). The main difference between these two methods is that the change in potential must be kept to less than ±25 mV for the LPR technique, while the change of potential can go up to ±250 mV for the TP technique. Another difference between LPR and TP is in the interpretation of testing results for the calculation of corrosion rate. In TP, corrosion rate can be calculated using straightforward substitution of Tafel slope values (β_a and β_c) to get the corrosion current and examined in Eq. (4) then, by calculating corrosion rate using Eq. (5)

$$i = i_{corr}\{\exp[S_1(E-E_{corr})] - \exp[-S_2(E-E_{corr})]\} \qquad (4)$$

where S_1=slope of the anodic branch=$2.303/\beta_a$, S_2=slope of the cathodic branch=$2.303/\beta_c$, β_a=anodic Tafel constant, β_c=cathodic Tafel constant, E_{corr}=the corrosion potential, i_{corr}=the corrosion current in Ampere, E=the potential at any time, and i=the current at any time.

$$\text{Corrosion rate} \ (\mu m/yr) = \frac{0.129 I_{corr} E.W.}{dA} \qquad (5)$$

where I_{corr}=the corrosion current intensity, in $\mu A/cm^2$; A=exposed surface area of the reinforcing steel, in cm; E.W.=the equivalent weight of steel, which is the atomic weight of an element that has the same combining capacity as a given weight of another element, where the standard is 8 for oxygen; and d=the density of the reinforcing steel, in g/cm^3.

To calculate the corrosion rate using the LPR method, I_{corr} is first calculated with Eq. (6) which is based on the Stern–Geary relationship. And then, using Eq. (5) the corrosion rate can be calculated [66,67].

$$I_{corr} = \frac{\beta_a \beta_c}{2.3 R_p (\beta_a \beta_c)}$$ (6)

where R_p is the polarization resistance, in $k\Omega cm^2$, and β_a and β_c are constants, which could be obtained from a Tafel Plot. To simplify the above calculation, some researchers have used Eq. (7) with a constant value, B, equal to 26 mV [68-72].

$I_{corr}=B/R_p$ (7)

This method offers the following significant advantages:
- Under idea conditions, the accuracy of the Tafel Extrapolation is equal or greater than conventional weight loss methods.
- With this technique it is possible to measure extremely low corrosion rates and it can be used for continuous monitoring of the corrosion rate of a system
- Tafel plots can provide a direct measure of the corrosion current, which can be related to corrosion rate.
- The rapid determination of corrosion rates with Tafel plots can be advantageous for such studies as inhibitor evaluations and alloy comparisons.

1.6   Galvanostatic Pulse Transient Method

Galvanostatic pulse method is a transient polarization technique working in the time domain. The method set-up is shown in Fig.7.
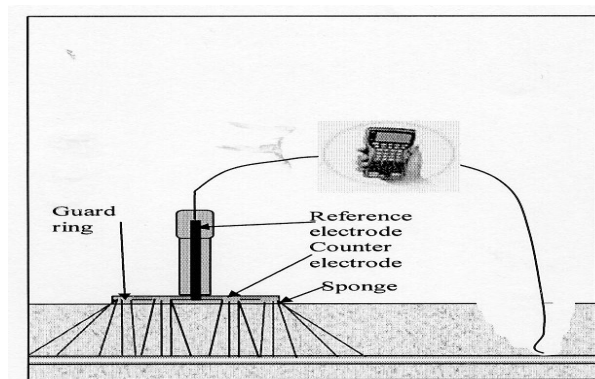

Figure 7. Set-up for galvanostatic pulse technique

A short time anodic current pulse is imposed galvanostatically on the reinforcement from a counter electrode placed on the concrete surface. The applied current is usually in the range of 10 to 200µA and the typical pulse duration is up to 10 seconds. The reinforcement is polarized in anodic direction compared to its free corrosion potential. The resulting change of the electrochemical potential of the reinforcement is recorded by a reference electrode (usually in the centre of the counter electrode) as a function of polarization time. Typical potential transient response is shown in Fig.8.
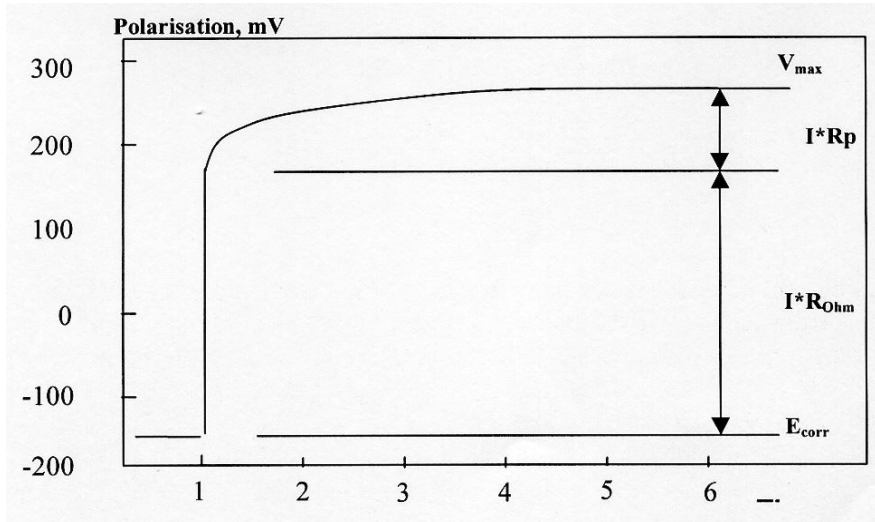

Figure 8. Typical potential-time curve as response to a galvanostatic pulse

When a constant current I_{app} is applied to the system, an intermediate ohmic potential jump and a slight polarization of the rebars occur. Under the assumption that a simple Randles circuit describes the transient behaviour of the rebars, the potential of the reinforcement, $V_t(t)$, at a given time t can be expressed as [73].

$$V_t(t) = I_{app}[R_p[1-\exp(-t / R_pC_{dl})]]+R_\Omega \qquad (8)$$

Where: R_p = polarization resistance

C_{dl} = double layer capacitance

R_Ω = ohmic resistance

In order to obtain the values of R_p and C_{dl} and the ohmic resistance R_Ω has to be evaluated further based on the experimental values. Two different methods, a linearization [74] and an exponential curve fitting procedure [75] have been proposed.   For the linearization eqn.(8) can be transformed in a linear form

$$\ln(V_{max}. - V_t(t)) = \ln(I_{app}R_p) - t / (R_pC_{dl}) \qquad (9)$$

where Vmax is the final (and experimentally unknown) steady potential value reached after long polarization. Extrapolation of this straight line to t = 0, using least square linear aggression analysis, yields an intercept corresponding to $\ln(I_{app}*R_p)$ with a slope of $l/(R_p*C_{dl})$. The remaining over potential corresponds to $I_{app}*R_\Omega$ which is the ohmic voltage drop.

One difficulty with the galvanostatic pulse transient technique is that the response to the pulse has to have stabilized to give an accurate value for V_{max}. Curtailing the measurements before an equilibrium value for V_{max} has been attained may also lead to errors in the evaluation of R_p and C_{dl}. This technique and those of AC impedance and harmonic analysis suffer from the same difficulty in measuring reinforced concrete structures in the field as does LPR measurement, i.e. the area of steel surface being measured is difficult to quantify.

1.7.   Electrochemical Impedance Spectroscopy (EIS)

In recent years, A.C. Impedance spectroscopy is being experimented as a useful non-destructive technique for quantifying corrosion of steel rebars embedded in concrete. Impedance Z is the ratio of A.C. voltage to A.C. current. An alternating voltage of about 10 to 20 mV is applied to the rebar and the resultant current and phase angle are measured for various frequencies.

The response to an A.C. input is a complex impedance that has both real (resistive) and imaginary (capacitive or inductive) component Z and Z" as shown in Fig.9. From studying the variation of the impedance with frequency, an equivalent electrical circuit can be determined which would give the same response as the corrosion system being studied.

Plotting the imaginary impedance against the real impedance gives a semicircle, with a diameter equal to Rt. The semicircle is offset from the origin by a value Rs, which is the ohmic resistance of the concrete cover zone between the reference half-cell and the reinforcing bar being measured. At the highest point on the semicircle the frequency f can be found and the double-layer capacitance value is then given by

$$C_{dl} = \frac{1}{2\Pi R_t f} \tag{10}$$

In practice, an AC Impedance response will often be a combination of several different semicircles, due to different RC parallel components, which could arise from film effects etc. The value of C_{dl} is useful because it may be used to the corrosion processes and which part is due to other processes.

The A.C. impedance technique has the advantage that it can give more information than DC LPR measurements, but it can be very time-consuming to perform and its use has been generally confined to the laboratory rather than on structures in the field [76]. The EIS is a powerful and general technique suitable for characterizing the electrochemical processes in inhomogeneous or multiphase materials. It can estimate a steady-state corrosion rate and subsequently [77]. EIS has been extensively used to evaluate the corrosion rate of the steel/concrete system. This technique may be very attractive because,

used in a wide range of frequencies; it can give detailed information about the mechanism and kinetics of the electrochemical reactions. Not only it is able to give R_{ct} (R_p) values, related to corrosion rate through the Stern–Geary formula, but also it may give complementary information on the corrosion process, the dielectric properties of the concrete (high frequency range) or the characteristics of the passivating film (very low frequency) [78]. Many researchers have used Impedance Spectroscopy for the characterization of the corrosion behaviour of steel in concrete [79-83]. An advantage of the EIS technique is the very small excitation amplitudes, generally in the range of 5 to 10mV peaks to peaks, minimally disturbs the steel, attached corrosion products or absorbed species during testing [84].
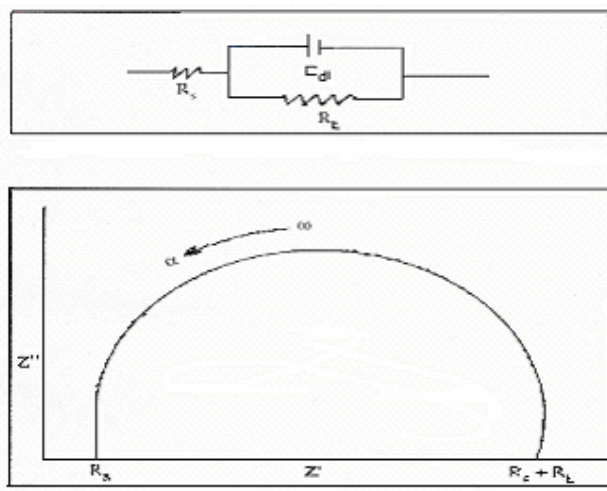

Figure 9. Nyquist Plot for steel in concrete

1.8   *Harmonic Analysis*

The harmonic analysis method is an extension of the impedance method. It is a relatively new technique, which is quicker to carryout and leads to results that are more straightforward than those of the electrochemical impedance method. This technique is carried out by applying an A.C. voltage perturbation V_0 at a single frequency and taking A.C. current density measurement i_1, and also measuring two higher harmonics i_2 and i_3 harmonic analysis as it is known uses the fact that the corroding interface acts as a rectifier, in that the second harmonic current response is not linear about the free corrosion potential [85]. The corrosion rate may be determined [86] from

$$I_{corr} = \frac{i_1^{\,2}}{\sqrt{48}\sqrt{2i_1 i_3 - i_2^{\,2}}} \qquad (11)$$

This test has the advantage that the Tafel constants can also be calculated from

$1/\beta_a$ or $1/\beta_c$ $= 1/2V_0 (i_1/ i_{corr} + 4i_2/i_1)$ (12)

The Tafel constants may then be used to calculate $B = \beta_a \beta_c/2.3(\beta_{a+} \beta_c)$ (13)

A simple amplitude sinusoidal voltage of 10 mV is applied to perturbate the working electrode in the same manner as the electrochemical impedance method. However only a single frequency is employed and the current response is measured in terms of the fundamental, first and second harmonics. This technique is quick and has the advantage over other electrochemical techniques in that it enables the calculation of the Tafel slopes (β_a and β_c) directly from the system under test. Since harmonic analysis is performed in a narrow frequency range, it can provide for practical and rapid rebar corrosion rate determination. A severe restriction of EIS and harmonic analysis is that, as in the LPR technique, the fundamental assumption of uniform corrosion has to be made in the calculation of penetration rates, If localized corrosion damage is actually taking place, the data is at best of a qualitative nature, indicating the breakdown of passivity and the possibility of localized attack.

1.9   Electrochemical Noise Analysis

Electrochemical noise technique is an emerging technique for monitoring corrosion of reinforced concrete structures [87]. This technique enables information on the mechanism and rate of corrosion processes at areas identified in concrete structures. A low amplitude variation of the corrosion potential of steel in concrete is measured to obtain a noise data as a record of potential fluctuations in the form of power spectra.

A noise source is located within the probable corroding area. A time record of sufficient interval is monitored over the frequency range (10 µHZ to Hz) noise data as a record of potential fluctuation is obtained. Noise signal is transformed from time domain to frequency domain displayed in the form of amplitude and frequency based on either fast fourier transform or maximum entropy method of spectral analysis. The measurement interval is usually between 2-10 seconds depending upon the frequency range.

The spontaneous, random fluctuations in current flow between two identical, electronically isolated bars in concrete coupled through a zero resistance ammeter are recorded, together with the fluctuations in the potential of one of them, measured against a reference electrode. The polarization resistance is then given by

$$R_p = \sigma_E/\sigma_I \qquad\qquad\qquad\qquad (14)$$

The corrosion rate may be obtained from R_p. In addition, the co-efficient of variance of the current noise σ_I/I is said to indicate the type of corrosion, ranging from 10^{-3} for general corrosion to 1.0 for localized corrosion [88].

A more modern version of the macro-cell current technique is electrochemical noise (EN), where besides the coupling current the voltage between the electrodes is also measured. EN consists of potential and current fluctuations spontaneously generated by corrosion reactions [89-91]. One of the most important advantages offered by this electrochemical technique is its lack of intrusiveness, i.e. its application does not involve artificial disturbance of the system. Various authors have claimed that, based on the results of these analyses, it is possible to characterize different corrosion types: metastable pitting, pitting and crevice corrosion, uniform corrosion, and stress-corrosion cracking [92-

94]. In order to assess the general characteristics of corrosion processes from the measured EN, several statistical parameters [95-96] (e.g. noise resistance) as well as parameters obtained from spectral analysis (e.g. noise impedance), are usually applied [97-98]. In some cases, various quantities defined by the theory of chaos have been implemented [99-100]. All these parameters are, however, calculated by means of mathematical techniques that are based on the assumption of the stationarity of the signals. EN signals, generated by various corrosion processes often do not satisfy the requirements for stationarity [101]. The only mathematical technique, which has been used for the analysis of measured EN, and does not require the stationarity of signals, is the wavelet transformation [102-103].

Only a few studies of EN for measuring corrosion in concrete have been performed [104-107]. In general, no distinct benefits of this technique comparing to the macro-cell current measurements were found. A comparison between some calculated parameters of measured EN and the corrosion rate did not, in many cases, give any clear results. Neither was correlation between specific EN fluctuations and the different stages in the corrosion processes quite clear. It was established that due to the low electrical conductivity of concrete and lengthy electrodes (rebars) some electro-magnetic disturbances could affect the measured EN signals.

1.10.1 Embeddable corrosion monitoring sensor

The Embedded Corrosion Instrument (ECI) is an electronic corrosion sensor that provides early warning of conditions that damage steel reinforcement, leading to cracking, spalling, and other deterioration of concrete structures. By monitoring five key factors in corrosion, and by communicating these through a digital network, the ECI provides comprehensive, real-time information on structural conditions. This helps facilities managers to avert crises, save money on maintenance, and build a detailed record on each structure. The ECI is designed to monitor bridges, buildings, dams, erosion control structures, flood control channels, parking garages, piers, pylons, roadways, and spillways. A non-destructive evaluation (NDE) device, it gathers and delivers all data without requiring inspectors to cut samples, interrupt use of a structure, or even visit the site. The ECI monitors five key factors in corrosion – linear polarization resistance, open circuit potential, resistivity, chloride ion concentration, and temperature. This provides more comprehensive data than prior generations of corrosion monitors. It also reveals correlations among the causes and signs of corrosion, yielding a fuller, more certain picture of the threat. The ECI integrate processing electronics with its sensors, and so can use digital, rather than analog communications. This eliminates data corruption by electro-magnetic interference from power lines, radio waves, and cellular telephones. Digital technology also makes it possible to connect multiple ECI monitors to a single data logger, saving potentially tens of thousands of dollars in support electronics per project. The ECI – 1 embeddable corrosion sensor incorporates 5 sensors into small rugged package that can be easily installed and placed wherever needed to provide adequate coverage of a structure during construction. The ECI-1 sensor (Fig.10) has much application in the construction and maintenance of commercial and civil structures [108].

Figure 10. ECI sensor during operation

1.10.2 Vibrating wire and electrical strain gauges

Conventional devices such as vibrating wire and electrical strain gauges have been demonstrated to exhibit good strain measuring capability and have been used successfully in structural health monitoring, vibrating wire strain gauges can be embedded in concrete to measure strain caused by stress variations. The stress can also be evaluated when the concretes modulus of elasticity is known, taking into consideration thermal, creep and concrete reaction effects. The advantages of the vibrating wire include its long-term reliability for absolute strain measurement and the ability of the frequent signal to be transmitted over long distances. The vibrating wire strain gauge can in principle be used to detect the formation of internal cracks and delamination in concrete. Electrical strain gauges, on the other hand, are not suited for monitoring propagation of internal cracks in concrete, since the formation of a crack, which intersects across these foil sensors, would render them unsafe. Furthermore, electrical strain gauges require bonding surfaces and therefore cannot be readily embedded in the volume of the concrete mix for detection of cracks and delamination.

Figure 11. Installation of VW strain guage

1.10.3 Optical fibre sensors

   In applications where strain measurements are not required for the assessment of the health of the structure, intensity based optical fiber systems are clearly attractive. In recent years, the use of optical fibre sensors for health monitoring of concrete structures has been a subject of intense research for monitoring corrosion, strain, displacement, opening of micro cracks and detection of cracks in concrete [109-116]. These studies, employing a variety of optical fibre sensors including fiber optic spectroscopy [109,113,114], fibre optic Bragg gratings [110-112] and intensity – based optical sensors [115,116] provide a clear demonstration of the potential of optical fiber sensor technology for structural health monitoring of civil engineering structures. Recently plastic optical fibers have been attracting a considerable amount of interest due to a number of reasons including their low cost, ease of termination and coupling and their relatively high resistance to fracture [115].

1.11   Cover Thickness Measurement

A covermeter or profometer is used for measuring concrete cover. By means of this it is able to detect rebar size, direction and position. Measurements are based on the damping of a parallel resonant circuit. An alternating current with a given frequency flows through the probe coil, thus creating an alternating magnetic field. Metal objects within the range of this field alter coil voltage as a function of cover and bar diameter. It comprises of a probe and an indicator unit. The electronic system, controls, indicator instruments are assembled on the indicator joint front panel. Eleven different bar diameter may be set in a rotary selector switch with a range from 8 to 34 mm. By means of this, the maximum cover thickness that can able to be measured is 120 mm. A loud audio signal and bright light on the detection head gives a clear warning of areas of low concrete cover (user programmable for depth of cover). Fig.12 shows the cover meter used for measuring the cover thickness as well diameter and size of the rebar.

Figure 12. Cover meter

The location of primary and secondary reinforcing bars is accomplished by moving the instrument along the surface of the concrete. The meter needle will indicate a maximum deflection when the axis of the instrument is parallel to and directly over the axis of a reinforcing bar or a group of bars. Investigations revealed that a minimum of 40mm is necessary for marine exposure and a 50mm cover

will be optimum [117]. However cover thickness of 70mm and 100mm have also been recommended for structures exposed to marine environment [118, 119]. Clear and Kay [120] mentioned the importance of concrete quality and adequate cover in combating corrosion. They recommended a clear cover thickness of 50mm with concrete having a w/c ratio of 0.40 and 75mm cover with concrete having a w/c ratio of 0.50. Cover thickness is an important parameter that preserves the electrochemical stability of steel in chloride contaminated concrete.

1.12   Ultrasonic Pulse Velocity Measurement

Ultrasonic Pulse Velocity (UPV) is a non destructive technique involves measuring the speed of sound through materials in order to predict material strength, to detect the presence of internal flaws such as cracking, voids, honeycomb, decay and other damage [121-123]. The technique is applicable where intrusive (destructive) testing is not desirable and can be applied to concrete, ceramics, stone and timber. The main strength of the method is in finding general changes in condition such as areas of weak concrete in a generally sound structure. Absolute measurements should be done carefully. At the same time, the UPV technique is not always practicable in testing sound concrete. Especially in investigation of crack depth, it is ineffective if the crack is water filled. The performance is also often poor in very rough surfaces. Sometimes good contact requires the use of a coupling gel between the transducers and the structure.

Sound energy above the audible frequency of 16,000 Hz is designated as ultrasonic. It is a form of mechanical energy and propagates through the material as stress waves by direct and intimate mass contacts without any bodily movement of the material. Pulses of longitudinal, elastic stress waves are generated by an electro-acoustical transducer that is held in direct contact with the surface of the concrete under test. After traversing through the concrete, the pulses are received and converted into electrical energy by a second transducer. Most standards describe three possible arrangements for the transducers:

1. The transducers are located directly opposite to each other (direct transmission)
2. The transducers are located diagonally to each other; that is the transducers are across corners (diagonal transmission).
3. The transducers are attached to the same surface and separated by a known distance (indirect transmission).

Pulses emitted by a transducer are transmitted through the material and received by another transducer, which is located at distance of 'L' from the transmitting transducer. The transmit time 'T' in microseconds of the first pulse arriving at the receiver is precisely measured by electronic means. From these physical parameters pulse velocity can be calculated as follows:

Pulse Velocity, $V = L / T$

The interpretation of data is very difficult as a large number of factors affect the pulse velocity [124]. The relationship between ultrasonic pulse velocity and the quality of concrete is given as follows in Table 4.

Table 4. Longitudinal pulse velocity vs. quality of concrete

Longitudinal pulse velocity (km/sec.)	Approximate compressive strength (N/mm^2)	Quality of concrete
Below 2.0	---	Very poor
2.0 to 3.0	4.0	Poor
3.0 to 3.5	Upto 10	Fairly good
3.5 to 4.0	Upto 25	Good
4.0 to 4.5	Upto 40	Very good
Above 4.5	Upto 40	Excellent

There exist many testing methods based on pulse-transmission, pulse-echo, impact-echo, and resonance techniques [125,126]. The strength of concrete increases with age and it is thus important to predict its value at any given stage of a construction process. Many investigations have shown a correlation between the increase of the speed of ultrasound and the increase of equivalent strength of concrete with age [127].

Amongst the many known instruments in this field is an instrument called PUNDIT, it uses the through transmission method to determine material characteristics in specially made samples of young or hardened concrete. It generates low-frequency ultrasonic pulses and measures the time taken for them to pass from one transducer to the other. It has become part of many national standards for concrete testing [128] and research [129].

Many investigations [130] and [131] have used high-frequency ultrasound (0.5–1 MHz), to quantify chemical damage in concrete. Using attenuation of surface waves, it was shown that it was possible to detect and characterize cover degradation. Young mortar and concrete were tested in this way after being subjected to chemical degradation at different periods of the hardening process. Synthetic aperture focusing techniques (SAFT) [132] have also received recent attention. This is a solution to the problem of flaw detection in concrete with single-sided access. SAFT uses a pulse-echo method based on the application of multiple source and receiver locations. Data processing algorithms are then applied which tend to reduce noise and increase image quality over that obtainable from a single transducer. This could be exploited in determining the time of flight of back wall echoes when testing loose concrete samples.

A different approach to the problem of concrete testing is the use of broadband ultrasonic electrostatic transducers, designed to operate in air [133]. Air coupling has obvious advantages in terms of scanning, and the ability to perform tests at a range of unprepared surfaces for both young and

hardened concrete. The main disadvantage of this technique is the much reduced signal amplitudes in concrete.

Another method for evaluating the elastic properties of young concrete uses an indirect measure of transverse waves by first knowing the velocity of Raleigh waves [134]. It is done with the help of two compression probes put on the same surface of the sample under test. The stress waves are generated with a hammer impact close to the transducers. Another study proposed the use of spectral analysis of surface waves to evaluate the compressive strength of single-layer high-strength concrete slabs through a correlation with the surface wave velocities

Grosse and Reinhardt [135] proposed two separate devices for young mortar and concrete measurements. The first one is based on pulse excitation by an impactor, and the second used two separate transducers for transmitting and receiving waves. Special software was developed that is able to do online data analysis using both Fourier and wavelet transforms.

Due to the complex and difficult nature of concrete, extensive use of signal processing techniques and modeling of the propagation of stress waves is needed in order to improve the response and increase the accuracy of current testing systems [136-138].

1.13.   X-ray /Gamma Radiography

Radiography technique is one of the non-destructive methods of testing concrete for obtaining information about concrete quality, defects within the reinforced concrete structures. Use of radioactive isotopes for concrete testing has been employed in γradiography studies. Radiography technique is reported to be a reliable method of locating internal cracks, voids and variation in density of concrete. Radiographic methods are classified into two types. The first one is using x-rays and other using γ rays. X-rays and γ-rays are invisible electromagnetic radiation, which can penetrate concrete and travel in straight line. Rays attenuate depending on nature, density and thickness of concrete. The principle of radioscopy is that the emission of photons by the radiation generator is transformed in visible light by a fluometallic converter for attaining maximum energy.   Photograph of the concrete is produced from which defects in reinforcements, cracks, voids, etc are identified. Radiations being dangerous, extra precautionary measures are to be taken.

Radiographic examination of prestressed concrete box girder bridges using high energy x-radiography was found to be useful to distinguish between grouted and ungrouted portions of cable sheaths; to find out the uniformity of the cement grout; to determine the condition of the cable sheath; and to determine whether the prestressing strands are snapped or intact.

2.14.   Infrared Thermograph

This technique is a new technique for acquiring the information about chloride content. This system consists of near – infrared irradiation equipment, imaging spectroscope and near-infrared multi spectrum camera. Dispersed near-infrared rays through the spectroscope can be received in each wavelength by light sensitive element on multi spectrum camera. Fig.13 shows the measurement and result of multi-spectrum camera [139].

Figure 13. Measurement and result of multi-spectrum camera

The sodium chloride was applied to the target specimen on surface area. Electromagnetic waves are absorbed or reflected from any substance depending on the characteristics of their components. Using this principle, the characteristic reflectance spectrum with a wavelength of 1640nm (1630nm -1650nm) in case of sodium chloride was acquired. This technique is a very effective and useful technique in order to acquire the chloride content on the surface of concrete.Fig.14 shows the prediction result of apparent diffusion coefficient by using thermograph [140].
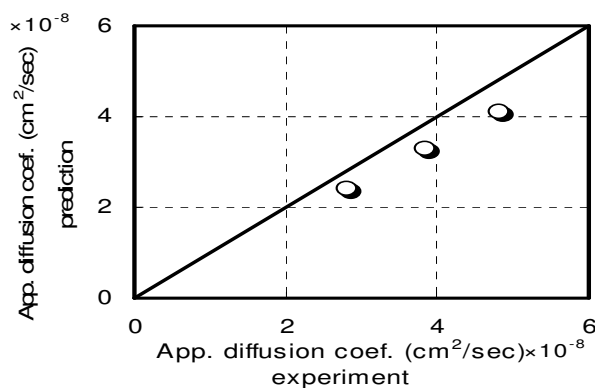

Figure 14. Prediction result of apparent diffusion coefficient by using thermograph

This method is based on that there is a good correlation between apparent diffusion coefficient of chloride ion and the heat dissipation characteristics of concrete. Although this technique is also under development, it is thought that it is a very effective technique in order to acquire the apparent diffusion coefficient of chloride ion without destroying concrete.

1.15   Visual Inspection

Visual inspection is done to inspect the structures visually, sometimes with the help of binoculars, once a month, once a year, or once in several years, according to the importance and the time after the structure is completed. In some cases, sonic inspection is carried out along with hammers in order to assess the soundness of concrete. The periodic inspection covers the visual information data such as cracks, rust stains, quality of concrete, spalled concrete cover, exposed reinforcement etc.

2. CONCLUSIONS

1. A number of electrochemical rebar corrosion measurement techniques available presently are reviewed. Each technique is reviewed to possess with certain advantages and limitations. To obtain maximum information about the corrosion state of rebar in a particular structure, a combination of measuring techniques is recommended. Although the electrochemical corrosion measurements are usually qualitative and also semi quantitative, significant benefits can be derived from them.

2. The development of durable, embeddable sensors and inexpensive microprocessor control and communications, have encouraged the development of corrosion monitoring systems for new and existing reinforced concrete structures. The development of integrated monitoring systems for new and existing reinforced concrete structures could reduce costs by allowing a more rational approach to the assessment of concrete structures.

3. The ability to continuously monitor the cover concrete and steel *in real time* could thus able to provide more information of the current and future performance of the structure.

4. Corrosion monitoring can be a vital part of planned maintenance and life prediction by giving quantitative information about the development of corrosion as aggressive conditions develop in the concrete due to chloride ingress or carbonation. It can also be used to assess the effectiveness of rehabilitation systems such as coatings or corrosion inhibitors. Installations have been carried out on new structures with long life requirements for planned maintenance and to prevent premature repair requirements.

5. Sensors are also used on structures exhibiting corrosion as part of a rehabilitation strategy to assess the effectiveness of repairs and to determine the future repair cycle.

6. The deployment of sensor systems, such as those described, to assess cover concrete and steel performance forms the important component of an integrated monitoring system. It is now recognized that in the total management of structures, which involves both whole life economics and life cycle estimations. Integrated monitoring systems and procedures have an important role to play. Monitoring systems can consist of sensors to measure the corrosion rate and concrete condition.

References:

1) M. Raupach and P. Schießl, *NDT&E Int.* 34 (2001) 435
2) A. Bentur, S. Diamond and N.S. Berke, *Steel corrosion in concrete: fundamentals and civil engineering practice*, E & FN Spon, London (1997).
3) B. Elsener, M. Buchler, F. Stalder and H. Bohni, *J. Corros.* 55 (1999) 1155
4) M.F. Montemor, A.M.P. Simoes and M.G.S. Ferreira, *Cem. Concr. Compos.* 25 (2003) 491
5) M. Saremi and E. Mahallati, *Cem. Concr. Res.* 32 (2002) 1915

6) ASTM C876-91(1999) *Standard test method for half-cell potentials of uncoated reinforcing steel in concrete.*
7) H.R.Soleymani and M.E.Ismail, *Cem. Concr. Res.* 34 (2004) 2037
8) B. Elsener, M. Molina and H. Bonhi. *Corros Sci* 35 (1993) 1563
9) B.Elsener, H.Bönhi In: N.S.Berke, V.Chaker, D.Whiting, editors. Corrosion rates of steel in concrete. *ASTM STP* 1065, Philadelphia, USA, 1990, p. 143
10) J.P.Broomfield, P.E.Langford, A.J.Ewins In: NS.Berke, V.Chaker, D.Whiting, editors. Corrosion rates of steel in concrete. ASTM STP 1065, Philadelphia, USA, 1990, p. 157
11) B. Elsener and H. Bönhi. *Mater Sci Forum* 111/112 (1992) 635
12) H.Arup. In: A.P.Crane, editor. *Corrosion of reinforcement in concrete construction. London,* UK, 1983, p. 151
13) R.D.Browne, M.P.Geoghegan and A.F.Baker, In: A.P.Crane, editor, *Corrosion of reinforcement in concrete construction. London,* UK, 1983, p. 193
14) J. Flis, H.W. Pickering and K. Osseo-Asare. *Electrochim. Acta* 43 (1998)1921
15) K. Videm, *Corrosion of reinforcement in concrete. Monitoring, prevention and rehabilitation.* EFC no. 25. London, 1998, p. 104–121
16) A. Aguilar, A. Sagüés, R. Powers, Corrosion rates of steel in concrete, in: N.S. Berke, V. Chaker, D. Whiting (Eds.), ASTM-STP 1065, *American Society for Testing and Materials, Philadelphia,* 1990, p. 66–85
17) E. Escalante. In: C.L.Page, K. Treadaway and P. Bamforth, Editors, *Corrosion of Reinforcement in Concrete*, Elsevier Applied Science, London–New York (1990), p. 281.
18) A. Sagüés, Corrosion measurement techniques for steel in concrete. *Corrosion 93, Paper 353.*
19) S.Erdogdu, I.L.Kondratova and T.W.Bremner, *Cem. Concr. Res.* 34(2004) 603
20) Yoon-Seok Choi, Jung-Gu Kim, Kwang-Myong Lee, Corrosion behaviour of steel bar embedded in fly ash concrete, *Corr. Sci.* 2005-In Press.
21) M.F.Montemor, M.P.Cunha. M.G.Ferreira and A.M.Simoes, *Cem.Concr.Comp.* 24(2002) 45
22) A.M.P.Simoes, M.M.Salta, *Cem.Concr.Comp*. 22(2000) 175
23) N.Asrar, A.U.Malik, S.Ahmad, F.S.Mujahid, *Constr. Build .Mater.*,13(1999)213
24) W.Yeih and R.Huang, *Cem.Concr.Res*. 28 (1998) 1071
25) Protection of reinforcement in concrete – An update, Galvanizing and other methods – Published by Indian Lead Zinc Information Centre (ILZIC), New Delhi, 1995. p.36.
26) N.S.Berke, M. Hicks, in: V. Chaker (Ed.), Corrosion forms and control for infrastructure, V.Chaker editor, *ASTM STP 1137, American Society of Testing and Materials, Philadelphia, 1992,* p. 207.
27) C. Andrade, C. Alonso, S. Goñi, in: R.K. Dhir, M. Roderick Jones (Eds.), *Proceedings of Conference Concrete 2000, Scotland, UK*, 1993, p. 1639.
28) S. Millard, J. Harrison and A. Edwards. *Br. J. Nondestructive Testing* 31 (1989) 616.
29) S. Feliu, J.A. Gonzalez, S. Feliu, Jr. and C. Andrade. *Brit. Corros. J.* 24 (1989) 195.
30) G. Glass, C. Page and N. Short. *Corros. Sci.* 32 (1991) 1283.
31) W. Lopez and J.A. Gonzalez. *Cem. Concr. Res.* 23 (1993) 368.
32) B.B. Hope, A.K. Ip and D.G. Manning. *Cem. Concr. Res.* 15 (1985) 525.
33) R.F. Stratfull. *Mater. Protect.* 8 (1968) 29.
34) R.D.Browne, *Durability of Building Materials*, 1(1982) 113.
35) W. Morris, A. Vico, M. Vazquez and S.R. De Sánchez. *Corros. Sci.* 44 (2002) 81.
36) S.E. Hussain, M. Rasheeduzzafar, A. Al-Musallan and A.S. Al-Gahtani. *Cem. Conc. Res.* 25 (1995) 15.
37) B.B. Hope, A.K. Ip and D.G. Manning. *Cem. Conc. Res.* 15 (1985) 525.
38) P.G.Cavalier, P.R.Vassie, Investigation and repair of reinforced corrosion in a bridge deck: *In Proceedings of Institution of Civil Engineers* Vol.70, Part 1 Auguest 1981 p.461-480.

39) K.C.Clear, "Time to corrosion of reinforcing steel in concrete slabs", Report No. FHWA/RD-82/028, *Federal Highway Administration, Washington*, D.C., 1982.

40) B.Tremper, J.L.Beaton, R.F.Stratfull, Causes and repair of deterioration to a California bridge due to corrosion of reinforcing steel in a marine environment, Part II, Fundamental factors causing corrosion, *H.R.B. Bulletin* 182, Washington, D.C., 1958, 18-42.

41) F.Hunkeler, The essentials for reinforced concrete monitoring, particular emphasis on cathodic protection onset and future responses. Conference on structural improvement through corrosion protection of reinforced concrete, *Institute of Corrosion,* 2–3 June, London, 1992.

42) R.B.Polder, P.C.Nuiten, Design and installation of a multi-element cathodic protection system. In: DWS Ho and F.Collins. editors, *Proc. RILEM International conference on rehabilitation of concrete structures. Melbourne,* 1992:257–66.

43) R.B.Polder and P.C.Nuiten, *Mater Perform.,* 33 (6) (1994)11

44) R.B.Polder, A.J.V.Hondel, Electrochemical realkalisation and chloride removal of concrete; state of the art, laboratory and field experience. In: D Ho, F. Collins editors. *Proc. RILEM, International conference on rehabilitation of concrete structures, Melbourne,* 1992:135–148.

45) J.P. Broomfield, Techniques to assess the corrosion activity of steel reinforced concrete structures. In: N.S. Berke, E. Escalante, C.K. Nmai and D. Whiting editors, *ASTM STP* 1276 (1996), p. 91–106.

46) K.R. Gowers, S.G. Millard, J.S. Gill and R.P. Gill. *Brit Corr J* 29 (1994) 25

47) K.R. Gowers, S.G. Millard, J.S.Gill. NACE, Corrosion 92, Paper 205.

48) K.C. Clear. *Transport Res Record* 1211 (1989) 28

49) M. Stern and A.L. Geary. *J Electrochem Soc* 104 (1957) 56

50) K.R. Gowers, S.G. Millard, J.S. Gill and R.P. Gill. *Brit Corr J* 29 (1994) 25

51) S. Feliu, J.A. Gonzalez, C. Andrade and V. Feliu. *Corrosion* 44 (1988) 761

52) S. Feliu, J.A. Gonzalez and C. Andrade. *ACI Special Publication* SP151-10 (1994) 183

53) S. Feliu, J.A. Gonzalez, S. Feliu, Jr and C. Andrade. *ACI Mat J* 87 (1990) 457

54) S. Feliu, J.A. Gonzalez and C. Andrade. *J Appl Electrochem* 26 (1996) 305

55) J.P.Broomfield, J.Rodriguez, L.M.Ortega, A.M.Garcia, *Structural Faults and Repair*, Edinburgh. 1993; p.155-163.

56) S.C. Kranc and A.A. Sagues. *Electrochim Acta* 38 (1993) 2055

57) A. Sehgal, D. Li, Y.T. Kho, K. Osseo-Asare and H.W. Pickering. *Corrosion* 48 (1992) 706

58) KR.Gowers, SG.Millard, JH.Bungey, British Institute of N.D.T., *International Conference on Non Destructive Testing in Civil Engineering* 97, 1997;1:361–382..

59) S.G.Milliard, D.W.Law, J.H.Bunsey and J.Cairus, *NDT & E International*, 34 (6) (2001) 409

60) C.Andrade, M.C.Alonso, J.A.Gonzalez, An initial effort to use corrosion rate measurements for estimating rebar durability corrosion rates of steel in concrete, *ASTM STP* 1065, N.S.Berke et al. editors. ASTM, Philadelphia 1990. 29-37.

61) M.G.Grantham and J.Broomfield, *Construction and Materials* 11 (1997) 215

62) ACI 222R-01, Protection of Metals in Concrete Against Corrosion, *American Concrete Institute,* Michigan, USA, 2001, p. 25.

63) D.A. Jones, Principles and prevention of corrosion. , Prentice-Hall, Upper Saddle River, NJ (1996).

64) J.L. Dawson, Electrochemical methods for the inspection and monitoring of corrosion of reinforcing steel in concrete. In: C.L. Page, K.W.J. Treadaway and P.B. Bamforth, editors, *Corrosion of Reinforcement in Concrete Structures*, Elsevier, London (1990), published for the Society of Chemical Industry. p. 358–371.

65) R.F. Stratful, W.J. Jurkovich and D.L. Spellman, Corrosion testing of bridge decks. *Transportation Research Record* vol. 539, Transportation Research Board, National Research Council, Washington, DC, USA (1975).

66) M. Stern and A.L. Geary, *J. Electrochem. Soc.* 104 (1) (1957) 56.

67) F. Mansfeld. In: Polarization Resistance Measurement, Electrochemical Techniques for Corrosion, National Association of Corrosion Engineers, Houston (1977), p. 18–26.

68) C. Andrade and J.A. González, *Werkst. Korros.* 29 (1978) 515

69) J. Flis, S. Sabol, H.W. Pickering, A. Sehgal, K. Osseo-Asare and P.D. Cady, *Corrosion* 49 (7) (1993) 601

70) D. Bjegovic, B.A. Milsic and R.D. Stehly, *Mater. Corros.* 51 (2000) 425

71) W. Morris, A. Vico, M. Vazquez and S.R. de Sanchez, *Corros. Sci.* 44 (2002) 81

72) M.A. Pech-Canul and P. Castro, *Cem. Concr. Res.* 32 (2002) 491

73) C.J.Newton, J.M.Sykes, *Corros. Sci.,* 28 (1988) 1051

74) B.Elsener, O.Klinghoffer, T.Frølund, E.Rislund, Y.Schiegg, H.Böhni: Assessment of reinforcement corrosion by means of galvanostatic pulse technique, *Proceedings of the International conference on Repair of concrete structures, from theory to practice in a marine environment*, Svolvaer, Norway, May 1997, 391-400.

75) B.Elsener, *Material Science Forum*, 192-194 (1995) 857

76) D.MacDonald, Evaluation of electrochemical impedance technology for detecting corrosion of rebar in reinforced concrete, National Research Council, Washington, DC-1991, *SHRP- ID/UFR – 91-524 Vol.1.*

77) L. Dhouibi, E. Triki and A. Raharinaivo, *Cem. Concr. Compos.* 24 (2002) 35

78) C. Andrade and C. Alonso, *Constr. Build. Mater.* 10 (5) (1996) 315

79) P.Gu, Y.Gu, P.Xie and J.J.Beaudoin, *Cem. Concr. Res.* 24 (1994) 231

80) D.D.MacDonald, M.C.H.Mckubre and U.Macdonald, *Corrosion,* 44 (1988) 2

81) M.F.Montemor, A.M.P.Simoes, M.M.Salta, M.G.S.Ferreira, *Corr. Sci.* 35 (1993) 1571

82) S.C.Kranc and A.A.Sagues, *Electrochim. Acta* 38 (1993) 2061

83) P.Lay. P.F.Lawrence, N.J.M.Winkins and D.E.Williams, *J.Appl.Electrochem.* 15 (1985) 755

84) A.Husain, S.Al.Bahar, S.Abdul Salam, O.Al-Shamali, Accelerated A.C, *Desalination,* 16 (5) (2004) 377

85) S.Sathyanarayana, *Electro-analytical Chemistry and Interfacial Electrochemistry*, 62 (1975) 209

86) J.S.Gill, L.M.Callow, J.D.Scantlebury, *Corrosion* 39 (1983) 61

87) D.A.Eden and A.N.Rothwell, Electrochemical noise data: analysis, interpretation and presentation, *Conference on Corrosion/92, NACE International, Houston, TX,* 1992, Paper 292.

88) K.R.Gowers, S.G.Milliard, Electrochemical technology for corrosion assessment of reinforced concrete structures, Proc. Insane. *Civ. Engrs. Structs. and Bldgs*, 134 (1999) May 129-134.

89) P.C. Searson and J.L. Dawson. *J. Electrochem. Soc.* 135 (1988) 1908

90) D.A. Eden. *J. Electrochem. Soc.* 141 (1994) 1402

91) A. Legat and C. Zevnik. *Corros. Sci.* 35 (1993) 1661

92) U. Bertocci and F. Huet. *Corrosion* 51 (1995) 131

93) A. Legat and V. Dolecek. *Corrosion* 51 (1995) 295

94) M. Leban, V. Dolecek and A. Legat. *Corrosion* 56 (2000) 921

95) R.A. Cottis. *Corrosion* 57(2001) 265

96) R.A. Cottis, M.A.A. Al-Awadhi, H. Al-Mazeedi and S.Turgoose. *Electrochim. Acta* 46 (2001) 3665

97) U. Bertocci, C. Gabrielli, F. Huet and M. Keddam, *J. Electrochem. Soc.* 144 (1997) 31

98) F. Mansfeld, C.C. Lee and G. Zhang, *Electrochim. Acta* 43 (1998) 435

99) A. Legat and V. Dolecek. *J. Electrochem. Soc.* 142 (1995) 1851

100) A. Legat, J. Osredkar, V. Kuhar and M. Leban. *Mater. Sci. Forum* 289–292 (1998) 807

101) M. Leban, A. Legat and V. Dolecek. *Mater. Corros.* 52 (2001) 418.

102) A. Aballe, M. Bethencourt, F.J. Botana and M. Marcos. *Electrochim. Acta* 44 (1999) 4805

103) J.A. Wharton, R.J.K. Wood and B.G. Mellor. *Corros. Sci.* 45 (2003) 97

104) U. Bertocci, in: J.R. Kearns, J.R. Scully, P.R. Roberge, D.L. Reichert, J.L. Dawson (Eds.), Electrochemical Noise Measurement for Corrosion Applications, *ASTM STP 1277, ASTM, West Conshohocken, PA*, 1996, p. 39.

105) L. Mariaca, A. Bautista, P. Rodriguez and J.A. Gonzales. *Mater. Struct.* 30 (1997) 613

106) M. Tullmin, C. M. Hansson, *Proceedings of the Corrosion1998*, San Diego, CA, NACE, Houston, TX, 1998, paper 372.

107) K. Videm. *Mater. Sci. Forum* 289-292 (1998) 3

108) Vti ${}_{TM}$ *Virginia Technologies Inc.www.vatechnologies.com*

109) P.L.Fuhr, D.R.Hustan, *Smart Materials and Structures*, 7(1998) 217

110) R.Maaskant, A.T.Alavie, R.M.Measure, G.Tadros, R.H.Rizkalla and A.Guha Thakurta, *Cem. Concr. Comp.* 19(1997) 217

111) M.A.Davis, D.G.Bellemore and A.D.Kersey, *Cem. Concr. Compos.* 19 (1997) 45

112) M.Maalej, A.Karasaridis, S.Pantazopoulou, D.Hatzinakos, *Smart Materials and Structures* 11 (2002) 581

113) B.Bonfiglioli and G.Pascale, *ASCE Journal of Materials in Civil Engg.,* 15 (2003) 125

114) L.Yuan and F.Ansari, *Measurement Science and Technology,* 9 (1998) 261

115) K.S.C.Kuang, Akmaluddin, C.J.Cantwell and C.Thomas, *Measurement Science and Technology* 14 (2003) 205

116) P.Rossi and F.Lemaou, *RILEM Materials and Structures*, 22 (1989) 437

117) K.S.Rajagopalan, S.Chandrasekaran, N.S.Rengaswamy and V.S.Muralidharan, *Indian Concrete Journal* 52 (9) (1978) 231

118) R.M.Weed, Recommended depth of cover for bridge deck steel, *Transportation Research Board*, Washington, KD.C 91974) 32.

119) B.F.McCollum, Design of Construction of conventional bridge decks that are resistant to corrosion, *Transportation Research Board*, Washington, 604, 1-5.

120) K.C.Clear and R.E.Kay. Time to corrosion of steel in concrete slabs, Vol.I, Effect of mix design and construction parameters, *FHWA Report No*. RD-73-22, *Interim Report FHWA,* April (1973).

121) H.W.Chung, *NDT International*, 18 (5) (1985) 275

122) J.Prasad, T.Rengacahry and N.S.murthy. Theory and practice of ultrasonic testing, Treatise on non-destructive testing and evaluation, K.Nair, editor, published by NDT centre, Central Laboratory, HAL Bangalore, Vol.2, May (1983) 5.

123) J.A.Forrester, Gamma radiograph of concrete, Paper No.2, symposium on Non destructive testing of concrete and timber, Institute of Civil Engineers, London, June (1969) 13.

124) C-597-83, Standard test method for pulse velocity through concrete, annual book of ASTM standards, Vol.4.02 (1989) p.289.

125) J. Krautkramer and M. Krautkramer, Ultrasonic testing of materials, Springer, Berlin (1990).

126) J. Blitz and G. Simpson, Ultrasonic methods of non-destructive testing, Chapman & Hall, London (1996).

127) K. Komlos, S. Popovics, T. Nurnbergerova, B. Babal and J.S. Popovics, *J. Cem. Concr. Compos*.18 (1996) 357

128) G. Lin, J. Lu, Z. Wang and S. Xiao, *Mag. Concr. Res.* 54 (2) (2002) 113

129) A. Fnine and F. Buyle-Bodin, Assessment of deteriorated concrete cover by high frequency ultrasonic waves, In: Proceedings of the international symposium on NDT in civil engineering, Berlin (2003).

130) S. Ould Naffa, M. Goueygou, B. Piwakowski and F. Buyle-Bodin, *J Ultrason* 40 (2002) 247

131) M. Schickert, Progress in ultrasonic SAFT-Imaging of concrete, In: Proceedings of the international symposium on NDT in civil engineering, Berlin (2003.)

132) J. Berriman, T.H. Gan, D.A. Hitchins and P. Purnell, Non-contact ultrasonic interrogation of concrete, In: Proceedings of the international symposium on NDT in civil engineering, Berlin (2003.)

133) A. Glaubitt, S. Bussat and J. Nuisance, Reference concrete for ultrasonic-testing and its creation by components with pre-analyzed properties. In: Proceedings of the international symposium on NDT in civil engineering, Berlin (2003.)

134) Y.S. Cho, *J Ultrason* 40 (2002) 227

135) C.U. Grosse and H.W. Reinhardt, New developments in quality control of concrete using ultrasound, In: Proceedings of the international symposium on NDT in civil engineering, Berlin (2003.)

136) J.S. Popovics, *J Acoust Soc Am* 98 (1995) 2142

137) S. Bussat, A. Glaubitt and J. Neisecke, Development of reference-samples for ultrasonic-testing of concrete. In: Proceedings of the international symposium on NDT in civil engineering, Berlin (2003.)

138) M.G. Hernandez, M.A.G. Izquierdo, A. Ibanez, J.J. Anaya and L.G. Ullate, *J Ultrason* 38 (2000) 531

139) D. Sato et al.: Measurement technique of acquiring sodium chloride concentration by using near-infrared spectrum, Proceedings of JSCE annual conference, Vol.56, pp.844-845, 2001.

140) Y. Kato et al.: Prediction of the resistance performance of the substance movement by using thermograph, Proceedings of JSCE annual conference, Vol.58, pp.825-826, 2003.