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NON-DESTRUCTIVE TESTING (NDT)

PART - 2

Dr. Fixit Institute

of Structural Protection & Rehabilitation

A Not-for-Profit Knowledge Centre

Non-destructive Testing (NDT)

In continuation to our efforts to create awareness on non-destructive testing for the durability of reinforced concrete structures, this issue of ReBuild is devoted to non-destructive techniques for corrosion measurement and monitoring.

Corrosion is a natural impact of marine, industrial and urban atmospheric environments on reinforcement steel which affects the structural stability of buildings and other built-in infrastructure. The annual loss due to corrosion can be compared with the loss due to other natural calamities like earthquakes and cyclones, only its impact is indirect. Loss due to corrosion can be 2% to 4% of GDP," said Houston-based National Association Corrosion Engineers (NACE) International president George Hays during his presentation at the NACE International India Section conclave in Mumbai recently. "As for the cost of corrosion in India alone, it is estimated to touch Rs. 36,000 crores," said Mr. Hays in the same conclave. The amount of money we are loosing due to corrosion can be invested in creating new infrastructure. Hence, corrosion monitoring and prevention should be a mandatory requirement for all new and old infrastructure. For all new structures a corrosion protection strategy should be incorporated by the designers in the beginning.

Non-destructive techniques detect the corrosion at an early stage. It can be used for quality control, maintenance, repair and restoration of reinforced concrete structures. There are many electrochemical and non-destructive techniques which can be used to monitor corrosion. The most commonly used NDT techniques are half-cell potential, Linear polarization resistance (LPR) measurement, the Galvanostatic pulse transient method, the Rapid Chloride Permeability Test (RCPT), Concrete resistivity measurement and Electromagnetic methods for locating rebar, etc.

But in this issue, we will only discuss Electromagnetic methods to locate rebar, the Galvanostatic pulse transient method and the Rapid Chloride Penetration Test (RCPT); their advantages, uses, limitations, accuracy and reliability.

The basic principle of the cover meter is the electro-magnetic field where any presence of steel affects the magnetic field and is detected by a sensor which gives a beeping sound. This helps to locate the rebar at the site exactly. The Profometer or cover meter is used mainly to locate the rebar for core cutting and measurement of cover depth of the concrete. The some of the advance equipment can also measure the diameter of the rebar, when the cover depth is known. Measurement of the cover depth will help calculate the onset of corrosion in new structures and the probability of extent of corrosion in old structures. The maximum range of measurement of such types of instruments is 100 mm beyond which it is not possible locate the rebar. In the case of congested reinforcement the accuracy level decreases.

The Galvanostatic Pulse Transient method is based on the measurement of polarization resistance, from which the rate of corrosion is calculated. A short duration current pulse is applied to the counter electrode and guard electrodes. Reference electrodes may be either Ag/AgCl or $Cu/CuSO_4$. It is most suitable to measure corrosion and predict corrosion of any reinforced concrete structures, which will help to estimate the service life of the structures. This will also help to map the corrosion to quantify the repair work exactly. The limitation of this equipment is that the pulse has to be stabilized to give an accurate value of voltage.

The Rapid Chloride Permeability Test (RCPT) measures electrical conductivity of the concrete to provide its resistance to the penetration of chloride ions, which depends on both the pore structure characteristics and pore solution of the concrete. The higher the charged Coulombs passed the higher the permeability. But the test results are influenced by the presence of Calcium Nitrate, Calcium Nitrite and Calcium Chloride which are usually present in certain admixtures. It does not measure permeability but measures resistivity of the concrete. Hence, a correlation has to be adopted between concrete resistivity and concrete permeability.

India has a vast coastline which comes under an extreme conditions category where reinforced concrete structures deteriorate very fast. Unfortunately in India we don't have a planned maintenance schedule for any buildings or infrastructure. So corrosion monitoring can be a vital part of planned maintenance where we can quantitatively measure the ingress of chloride or carbonation into the reinforced concrete structures. It can also be used to assess the effectiveness of repair and rehabilitation of a protective coating system or even of corrosion inhibitors.

We hope our readers will find this issue more useful and take some initiatives to monitor the corrosion and take a proactive step for suitable protection measures to increase the service life of reinforced concrete structures. We will focus on some more non-destructive equipment for the durability of concrete structures in the next issue of ReBuild.

Corrosion Measuring Techniques in Reinforced Concrete Structures

[By Sangeeta Gadve, Associate Professor, Department of Structural Engineering, Sardar Patel College of Engineering, Andheri (W), Mumbai]

1.0 Introduction

In a tropical country like India with more than 3000 kms of coastline and approximately 80% of the annual rainfall taking place in the monsoon, corrosion related problems are alarming. In metro cities, the carbon and nitrogen oxide emissions aggravate the situation further by neutralizing the concrete cover. A large proportion of such damage is caused due to insufficient planning and incorrect assessment of environmental attack such as carbonation and chloride exposure. The updated corrosion map of India (2004) (Fig. 1) was drawn by The Central Electrochemical Research Institute (CECRI), Karaikudi, based upon a scientific study conducted for a period of 10 years from 1993 to 2003 at 33 field stations in the country. Metal panels of different materials like mild steel, zinc, galvanized iron and aluminium were exposed to the air and annual corrosion rates in millimetres per year (mm/y) were determined in correlation with atmospheric pollutants and climatic factors. The most corrosion prone city was Sriharikota on the Andhra Pradesh coast. Chennai was the second most corrosion prone city in the country, due to its ever-increasing vehicle population and its coastal location. What this means is that those buildings in the city which have not been made especially corrosion-proof (or for that matter, even those vehicles which have not received an extra coat of anti-corrosion paint) might be in for considerable trouble. Similarly non-coastal Mettupalayam in Tamil Nadu was found to be among the five most corrosion-prone places in the country. Normally it is only coastal cities that are prone to corrosion. In the case of Mettupalayam, though it is considerably inland, it was found that a combination of rainfall, relative humidity and industrial pollution had been its bane. It was evident from this study that the corrosion was spot specific and not region specific.

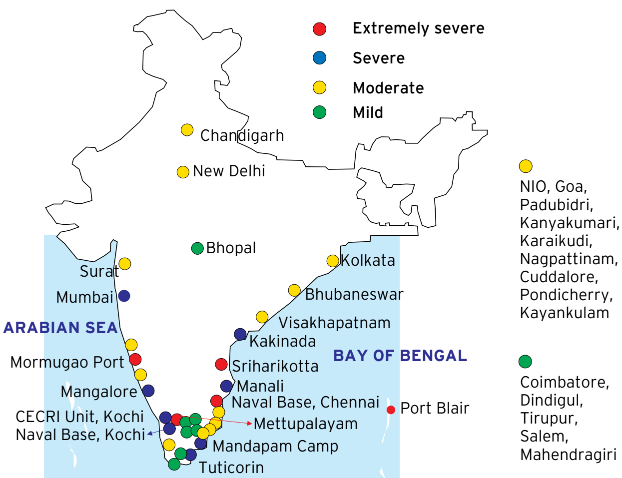

Fig. 1: Updated corrosion map of India (2004)

Based on the findings, three categories were drawn up: extremely corrosive (above 0.2 mm/y), corrosive (below 0.2 mm/y) and moderately corrosive. While Sriharikotta recorded 1.6mm/y, Chennai touched 0.5 mm/y, Mormogao 0.45 mm/y, Port Blair 0.38 mm/y and Mettupalayam 0.3 mm/y. The mild steel panel at the Chennai naval base, for example, was found to have decreased in size from 2.5mm to 0.5mm in just eight months. Under the corrosive category fell Manali, Mangalore, Kakinada, Mandapam, Tuticorin, Kochi and Mumbai. Hence it was evident those buildings and infrastructures in extreme cities affected by extreme environmental changes (Fig. 1), which have not been made especially corrosion-proof, or for that matter even those vehicles which have not received an extra coat of anti-corrosion paint, might be in for considerable trouble.

2.0 Corrosion-induced Deterioration

One major flaw of RC structures, namely its susceptibility to environmental attack, can severely reduce the strength and life of these structures. In humid conditions, atmospheric pollutants percolate through the concrete cover and cause corrosion of steel reinforcements. The resulting corrosion products occupy volumes several times that of the volume of steel. The increased volume induces tensile stress in the concrete that results in cracking, delamination and spalling. As a result, the reinforcements are exposed to direct environmental attack and the corrosion is accelerated. Along with an unpleasant appearance, it weakens the concrete structure to a high degree. Moreover, bond between the steel and the concrete is reduced. Pitting corrosion, which occurs due to chloride ingress through the pores of the concrete, may also reduce the ductility of the steel bar by introducing notches on the surface of the steel bars that leads to premature necking.

There are mainly two major causes of steel corrosion in concrete, i.e. chloride attack and carbonation. For corrosion to occur, steel reinforcing bars should be depassivated. Oxygen, water and aggressive ions, such as chlorides, need to be available and the concrete needs to have low resistivity. Also all these conditions must be present simultaneously. However, the intrusion of chloride ions is the most important factor in the corrosion of steel reinforcing bars embedded in concrete. Possible sources of chlorides include: aggregates, mix water, admixtures (accelerators) and seawater.

When carbon dioxide (CO_2) from the atmosphere penetrates concrete and dissolves in the pore solution, carbonic acid is formed. This acid reacts with the alkali in the cement to form carbonates and lowers the pH of concrete. When the alkalinity reaches a low enough level, the steel reinforcing bar become depassivated and, in the presence of sufficient water and oxygen, corrosion is initiated and propagated. However, carbonation advances very slowly in sound concrete and is generally not a big factor in corrosion initiation.

The corrosion products resulting from the corrosion of steel reinforcing bars occupy a volume three to six times that of the original steel. This increase in volume induces stresses in the concrete that result in cracks, delaminations and spalls. This further accelerates the corrosion process by providing an easy pathway for water and chlorides to reach the steel.

3.0 Corrosion Measuring Techniques

Several corrosion monitoring parameters, destructive as well as non-destructive in nature, can be studied. Even though destructive tests such as the bond test and the mass loss test are more dependable to accurately assess the corrosion, these tests are not desirable in-situ. Therefore, it becomes mandatory to implement non-destructive tests to monitor or assess the extent of corrosion. However, there is no single non-destructive technique which will quantify the extent of damage of structures at the outset and how rapidly the damage will grow with time. Therefore it is advisable to use more than one NDT technique to monitor corrosion. Table 1 presents the various methods of evaluation of corrosion and detection of the respective defects.

Table 1: Tests methods for corrosion evaluation

Methods	Detects
Visual Inspection	Surface defects
Hammering / chain dragging	Delaminations
Cover meter	Rebar depth (& size)
Phenolphthalein/Carbonation Test	Carbonation depth
Damages - Fire/ blast Chloride content	Chloride induced corrosion
Permeability Test	Diffusion rate
Impact/ultrasonic	Defects/Concrete quality
Petrography	Concrete properties
Half cell Potential	Corrosion risk
Linear polarization	Corrosion rate
Resistivity	Concrete resistivity

4.0 Visual Inspection

The critical visual inspection of the concrete structure gives a fair idea of the extent of corrosion. Some of the following observations are indicative of the initiation of corrosion from moderate to severe corrosion:

- The formation of white patches on the concrete surface indicates carbonation, which is one of the major causes of inducing corrosion in concrete structures.
- Brown or reddish patches of rust along reinforcements cause alarm to attend to the induced corrosion.
- Identifying corrosion cracks from structural cracks: if the cracks are formed along the reinforcement, they are indicative of corrosion since structural cracks are not formed along the reinforcements in the flexural member.
- A black coloured substance oozing through the cracks indicate severe corrosion and significant loss of steel.
- Bulging of the concrete at certain locations, on the surface, is also indicative of the occurrence of corrosion.

5.0 Chemical Analysis

5.1 Carbonation Test

The carbonation is one of the major causes of corrosion of reinforcement in the concrete, it becomes important to evaluate the depth up to which concrete has become virtually acidic. Depth of carbonation can be determined by a simple test in which a dilute phenolphthalein solution is sprayed on a concrete surface. As a result, carbonated concrete remains colourless and uncarbonated good concrete becomes pink in colour.

5.2 Chloride Contents

The minimum chloride ion concentration needed to initiate corrosion of steel reinforcing bars is also called the corrosion chloride threshold. Although the concept of a chloride threshold is generally accepted, there is disagreement on what shall be the threshold value. Several factors such as the composition of the concrete (resistivity), the amount of moisture present, and the atmospheric conditions (temperature and humidity) influence the chloride threshold value. The threshold concentration depends on the pH level and the concentration of oxygen also. Chlorides induce pitting corrosion in steel reinforcement at isolated points. However, when chlorides are uniformly distributed, higher concentrations are needed to initiate corrosion. Regardless of what concentration of chloride ions is needed to initiate corrosion, an increase in the chloride ion concentration increases the probability that corrosion of steel reinforcing bars will occur. In general, the concentration of chloride ions needs to be more than 0.71 kg/m^3. The presence of chlorides also increases shrinkage cracks in the concrete which may further accelerate corrosion of reinforcement in aggressive environment.

Drilling of concrete is carried out to obtain concrete powder samples for determination of chloride content. Total chloride content can be determined as per ASTM 1152 and may be compared with corrosion chloride threshold. As stipulated in IS: 456-2000, chlorides permitted in concrete are limited to 0.4 Kg/m^3 in prestressed concrete and 0.6 kg/m^3 in reinforced concrete.

6.0 Cover Meter

It is extremely necessary to provide adequate cover thickness to control corrosion. A Cover meter or Profometer is an instrument commercially available, used to measure the depth of concrete cover. It also gives the location of the reinforcing bars and diameter of the bar. The depth of cover concrete thus obtained can indicate the possibility of the onset of corrosion in new structures and the probable extent of corrosion in old structures. Further, the diameter of the bar indicates the loss of cross section if any, due to corrosion. Thus a cover thickness survey is useful to determine existing cover depth in a specified location, where damage has been identified and at other locations for comparison on the same structure. Table 2 shows how the cover readings may be interpreted for the assessment of corrosion.

Table 2: Interpretation of Concrete Cover Survey

Sr. No.	Test Results	Interpretation
1	Required cover thickness and good quality concrete	Relatively not corrosion prone
2	Required cover thickness and bad quality concrete cover	Corrosion prone
3	Very less cover thickness yet good quality concrete	Corrosion prone

7.0 Half-cell Potential

When steel corrodes in concrete, a potential difference is developed between the anodic and cathodic areas of the steel. This difference can be detected, by placing a standard reference electrode/cell (Half-cell) on the surface of the concrete. The potential difference between the reinforcing steel and the standard reference electrode can be measured giving an electrical connection to the reinforcing bar and observing the voltage difference between the bar and a reference electrode in contact with the concrete surface as shown in Figure 2. The half cell potential measurement gives an indication of the corrosion risk of the steel.

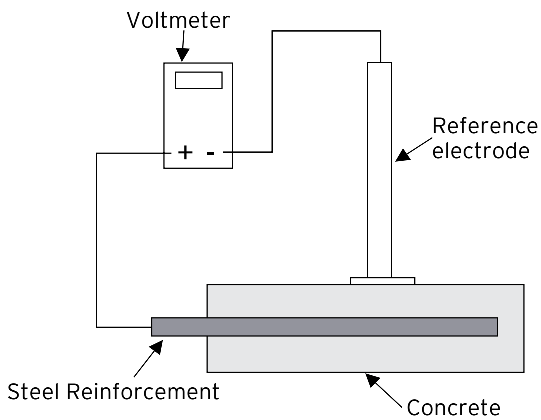

Fig. 2: Half-cell measurement of corrosion

Generally, as the corrosion activity is progressed, the potential becomes more and more negative. However, less negative potential may also indicate the presence of corrosion activity, if the pH values are less. As per ASTM C 876 standards, the probability of reinforcement corrosion is given in Table 3.

Table 3: ASTM C 876 guide for evaluation of corrosion activity

Corrosion risk	Half-cell potential (Vs Ag/AgCl)	Half-cell potential (Vs Cu/ $CuSO_4$)	Half-cell potential (Vs SCE)
Severe corrosion	Less than - 404 mV	Less than - 500 mV	Less than - 426 mV
High corrosion risk (90% probability)	Between - 404 mV and - 254 mV	Between - 500 mV and - 350 mV	Between - 425 mV and - 275 mV
Medium corrosion risk (50% probability)	Between - 254 mV and - 104 mV	Between - 350 mV and - 200 mV	Between - 275 mV and - 125 mV
Low corrosion risk (10% probability)	Higher than - 104 mV	Higher than - 200 mV	Higher than - 125 mV

This method has not proved to be effective if the potential measurement is carried out at random points on the structure and each reading is interpreted in isolation. However, a systematic "potential mapping survey" has proved to be more effective and useful for the assessment of rebar corrosion on-site. Corrosion potential mapping gives potential profile or potential contours. The potential contours are analyzed to identify the locations that indicate the extent of corrosion of rebar. The interpretation of results help to classify structural members into beams and columns with major damage that may need to reconstruct structural members that need rehabilitation, members with minor damage and so on. However, it is advisable to employ this technique coupled with measurements of chloride content of the concrete, the cover to the steel and the depth of carbonation, instead of employing these in isolation.

8.0 Linear Polarization Resistance Measurement

Linear Polarization Resistance (LPR) measurement is now a well-established method to determine the instantaneous corrosion rate measurement of the surface of a reinforcing bar in concrete. Linear polarization is simple in principle, although the underlying theory is complex and its use in practice is also complex. The theory of linear polarization relies on the relationship between the half cell potential of a piece of corroding steel and an external current applied to it. This means that the corrosion rate is proportional to the applied current divided by the potential shift.

This can be expressed by the equations:

$I_{corr} = B/R_P$ ------------------------------------(eq. 1)

Where, I_{corr} is the corrosion current

B is a Stern-Geary constant or a constant related to the anodic and cathodic Tafel slopes

R_P, the polarization resistance, $R_P = \Delta E / \Delta I$

ΔI is the change in current

ΔE is the change in potential

To measure R_P the surface of a reinforcing steel bar is polarized from its equilibrium potential by a small over potential, ΔE, usually in the range 10 to 30mV. The resulting current is then monitored at the end of a selected time period, usually between 30 seconds to 5 minutes. To evaluate the corrosion current density, Icorr, the surface area of steel that has been polarized needs to be accurately known. The corrosion rate may then be correlated to corrosion current density and mean corrosion penetration rate.

The relation between the corrosion current and corrosion classification as published in BRE (Building Research Establishment), UK. BRE Digest 434 is given in the Table 4.

Table 4: Relation between corrosion current and classification

Corrosion Current Density (mA/cm²)	Mean Corrosion Penetration Rate (mm/year)	Corrosion Classification
Up to 0.1 to 0.2	Up to 1 - 2	Very low or Passive
0.2 to 0.5	2 - 6	Low to moderate
0.5 to 1.0	6-12	Moderate to High
> 1.0	> 12	High

8.1 Measurement of LPR

Linear polarization (LP) is usually conducted in aqueous solutions on small, corroding specimens. A number of LP devices are now commercially available. The system consists of a half cell to measure the potential and its change, an auxiliary electrode to pass the current and a guard ring around the auxiliary electrode to constrain the electric field from the auxiliary electrode because of the size of the corroding rebar as shown in Figure 3.

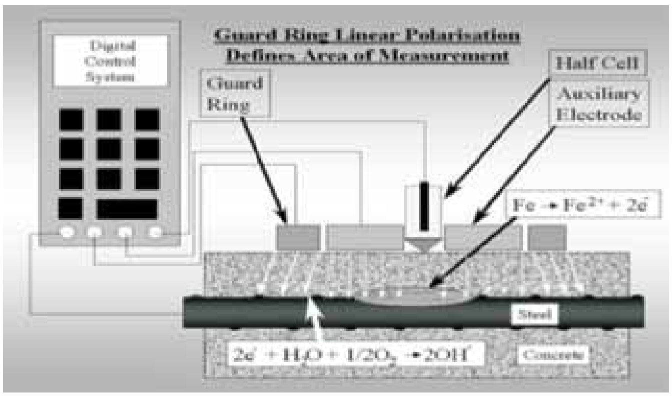

Fig. 3: Measurement of corrosion by linear polarization

9.0 Concrete Resistivity Measurement

The electrical resistance of concrete is an important property that decides the quality of concrete. This parameter is expressed in terms of "Resistivity" in ohm-cm. The long-term corrosion can be anticipated in concrete structure if the resistivity of the concrete can be accurately measured. Table 5 indicates the general guidelines of resistivity values based on which areas with probable corrosion risk can be identified.

Table 5: Corrosion risk from resistivity in concrete structures

Resistivity ohm-cm	Corrosion Probability
Greater than 20,000	Negligible
10,000 - 20,000	Low
5,000 - 10000	High
Less than 5,000	Very high

Electrical resistivity of concrete is determined essentially by using a 4-probe technique in which a known current is applied between two outer probes at least 100 mm apart and the voltage drop between the two inner elements at least 50 mm apart. This is read allowing for a direct evaluation of resistance, R. Using a mathematical conversion factor resistivity is calculated as per the principle of four probe resistivity testing as shown in Figure 4.

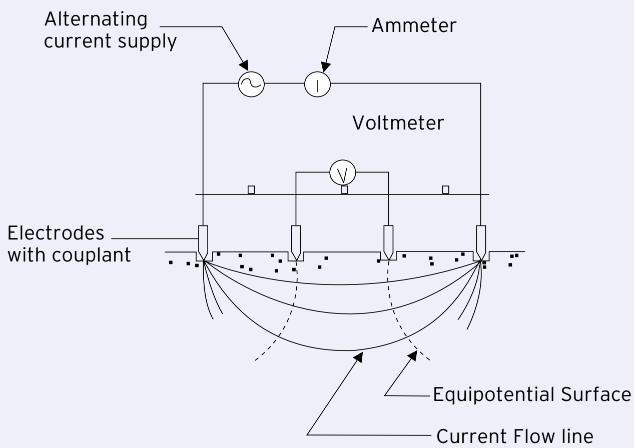

Fig. 4: Measurement of corrosion by Resistivity method

10.0 Conclusion

Corrosion affected reinforced structures are highly susceptible to catastrophic collapse. So it is necessary to estimate the rate of corrosion by different available techniques before designing for repairing due to corrosion related damages. The other aspects are quality control, maintenance and planning for restoration of such built-in structures where non-destructive inspections and measurement techniques can be used to detect the corrosion of reinforcement at an early stage. This would help to take suitable remedial measures to prevent corrosion, increasing their service lives and minimizing repair and maintenance cost.

Electromagnetic Testing Method of Rebar in Reinforced Concrete

[Excerpts from "Guidebook on Non-destructive Testing of Concrete Structures" Published by International Atomic Energy Agency, Vienna, 2002, pp.79-81]

1.0 Fundamental Principles

The basic principle is that the presence of steel affects a magnetic field. An electromagnetic search probe is swept over the surface of the concrete under test. The presence of reinforcement, within the range of the instrument, is shown by movement of the indicator needle.

The test is conducted either by utilizing the eddy current effect or magnetic induction effect. With covermeters using the eddy current effect, currents in a search coil set up eddy currents in the reinforcement which in turn cause a change in the measured impedance of the search coil. Instruments working on this principle operate at frequencies above 1 kHz and are thus sensitive to the presence of any conducting metal in the vicinity of the search head.

With covermeters using magnetic induction, a multi-coil search head is used with a lower operating frequency than the eddy current type of device (typically below 90 Hz). The principle used is similar to that of a transformer, in that one or two coils (the primary coils) carry the driving current while one or two other coils (the secondary coils) pick up the voltage transferred via the magnetic circuit formed by the search head and embedded reinforcing bar. Such instruments are less sensitive to non-magnetic materials than those using the eddy current principle. When there is a change to the amount of ferromagnetic material under the search head e.g. by the presence of reinforcing bars or other metal objects, there is an increase in the field strength. This results in an increase in the voltage detected by the secondary coil, which can be displayed after amplification by a meter.

In both types of instruments, the orientation and the proximity of the metal to the search head affect the meter reading. It is therefore possible to locate reinforcing bars and determine their orientation. The cover to a bar may also be determined if a suitable calibration can be obtained for the particular size of bar and the materials under investigation. Most instruments have a procedure to allow an estimate to be made of both bar size and distance from the probe to the bar when neither is known.

2.0 Equipment for Electromagnetic Inspection

A number of suitable batteries or mains operated covermeters exist. They comprise a search head, meter and interconnecting cable. The concrete surface is scanned, with the search head kept in contact with it (Fig. 1) while the meter indicates, by analogue or digital means, the proximity of reinforcement.

Fig. 1: Scanning of reinforcement by a Profometer

3.0 Calibration

Regular checks on the covermeter should be carried out to establish the accuracy of the instrument. A basic calibration method is given in BS 4408 part 1 involving a cube of concrete of given proportions, with reinforcing bars at specified distances from the surface. If different search heads are to be used with the same meter, calibration checks should be carried out for each head. Every instrument has a calibration block with a specified bar diameter and measured cover depth from diffrent sides which should be used for a calibration check. The Figure 2 shows a particular calibration block.

Fig. 2: Calibration block of Profometer

A site calibration of the covermeter can be carried out by drilling a series of test holes to the bars at positions representing different covers as found by the covermeter. Care should be taken not to damage the reinforcement. The distance between each bar and the concrete surface is then measured at each point using a depth gauge. A calibration curve can then be constructed comparing the actual depth with that given by the covermeter. In-situ covers are then calculated using the reference scale readings and this calibration curve.

It may be possible to take advantage of projecting reinforcement to check the performance of the covermeter.

4.0 Applications

Electromagnetic covermeters can be used for:

- Quality control to ensure correct location and cover to reinforcing bars after concrete placement.
- Investigation of concrete members for which records are not available or need to be checked.
- Location of reinforcement as a preliminary to some other form of testing in which reinforcement should be avoided or its nature taken into account, e.g. extraction of cores, ultrasonic pulse velocity measurements or near to surface methods.
- Location of buried ferromagnetic objects other than reinforcement, e.g. water pipes, steel joists, lighting conduits.
- Advanced versions of covermeter can also indicate bar diameter when cover is known.

5.0 Range and Limitations

The search head is traversed systematically across the concrete and, where reinforcement is located, rotated until a position of maximum disturbance of the electromagnetic field is indicated by a meter or by an audible signal. In such a position, under ideal conditions, the indicated cover to the nearest piece of reinforcement may be read if the bar size is known. Further, the axis of the reinforcement will then lie in the plane containing the centre line through the poles of the search head. Where reinforcement is not too congested, it is possible to map out all bars within the area under examination, which lie sufficiently close to the surface. It may also be possible to determine the position of laps. If the bar size is known, the cover can be measured. If the cover is known, the bar size can be estimated. In some equipment it is claimed to be possible to determine the concrete cover over the first layer of reinforcement and then, by using a spacer, estimate the size of the reinforcement used in that layer. It can not be too strongly emphasized that for maximum accuracy, interference from other reinforcement or magnetic material has to be avoided. If the concrete cover is in the range of 0 to 20 mm, which is less than the normal operating range of some instruments, the following procedure can be used. A 20 mm thick spacer of material inert to the covermeter, such as wood or plastic, is placed between the search head and the concrete surface. An apparent cover for the particular bar size is read directly from the meter and the indicated cover obtained by subtracting 20 mm from this value. This method is only suitable where the concrete surface is flat and smooth.

The limitations of the method are:

- It is very slow and labour intensive.
- The results are affected by the presence of more than one reinforcing bar in the test area, by laps, by second layers, by metal tie wires and by bar supports.
- For maximum accuracy it has to be calibrated for the concrete used in the structure to eliminate the influence of iron content of the aggregate and cement used.
- The method is unsuitable in the case of closely packed bar assemblies.
- The accuracy is reduced if rough or undulating surfaces are present, e.g. exposed aggregate finishes. The effect on the indicated cover will be similar in magnitude to the surface irregularities within the area of the search head.
- The maximum range of the instrument for practical purposes is about 100 mm.
- It does not give indication of the quality of concrete cover or the degree of protection afforded to the reinforcement.

6.0 Accuracy

The accuracy of reinforcing bar size estimation ranges from ± 2% to ± 15%. Therefore care must be taken in reporting a reinforcing bar size which differs from a design requirement, without seeking confirmation by exposing the bar. A bar size may only be able to be reliably estimated to within one bar size of the actual bar size.

- Calibrated meter scales are generally valid for a particular grade of reinforcing steel. The effect of different types of steel on the readings obtained is generally small but, in special cases, such as high tensile prestressing bars, it may include errors as high as ± 5% or more. Where such materials are present, the covermeter should be calibrated for the reinforcing steel used by constructing a calibration curve.
- To accurately measure cover and size, the bar has to be both straight and parallel to the concrete surface.
- Where significant corrosion to reinforcement has occurred, in particular scaling and migration of corrosion products, misleading indicated cover readings are likely to be obtained.
- Interference effects will occur in the neighbourhood of metallic structures of significant size such as window fixings, scaffolding and steel pipes, especially when they are immediately behind the search head. The degree of influence will depend on the particular covermeter used but all are affected by either stray magnetic fields or electric fields or both. In such cases reliable use of the instrument may be severely restricted.

Galvanostatic Pulse Transient Method for Corrosion Measurement and Service Life Estimation of RC Structures

[Source:http://www.germann.org/TestSystems/GalvaPulse/GalvaPulse.pdf]

1.0 Fundamental Principle

Reinforcement corrosion is evaluated by the corrosion rate stating how much steel is being dissolved in µm/year (10^{-3}mm/year). In addition, half-cell potentials and the electrical resistance of the cover layer are also measured with this instrument. The principle of the corrosion rate measurement is stated as per following.

An anodic current pulse "I" is imposed on the reinforcement from a counter electrode placed on the concrete surface. A guard ring confines the current to an area "A" of the reinforcement below the central counter electrode (Fig. 1). The applied current is usually in the range of 5 to 400 µA and the typical pulse duration is 5–10 seconds. The reinforcement is polarized in the anodic direction compared to its free corrosion potential. With an Ag/AgCl reference electrode, the resulting change of the electrochemical potential of the reinforcement is recorded as a function of time. A typical potential response for a corroding reinforcement is shown in Figure 2.

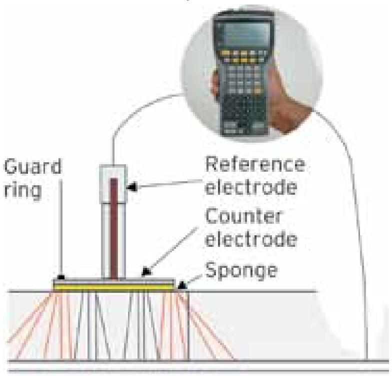

Fig. 1: Set-up for galvanostatic pulse technique

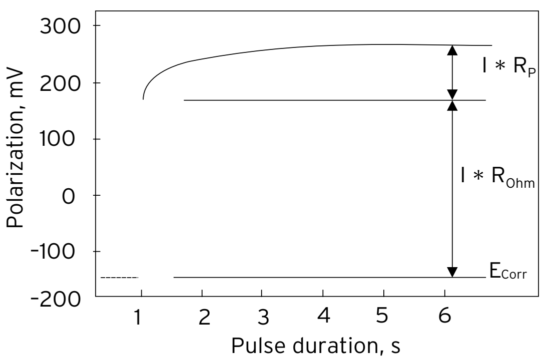

Fig. 2: Typical potential-time curve as response to a galvanostatic pulse

When the constant current "I" is applied to the system, an ohmic potential drop "$I*R_{Ohm}$" occurs and so does the polarization of the reinforcement "$I*R_P$". The polarization resistance of the reinforcement "R_P" is calculated. By means of the Stern Geary equation for active corrosion $I_{corr} = 26/R_P$ and Faraday's law of electrochemical equivalence, the corrosion rate is estimated as: Corrosion Rate = 11.6 * I_{corr} /A. Where as, the corrosion rate is given in µm/year (0.001 mm/year), "I_{corr}" is the corrosion current in µA and "A" the confined area of the reinforcement in cm^2 below the central counter electrode. The factor 11.6 is for black steel.

Following the testing the handheld computer is connected to a PC with installed Windows based viewing and reporting software. The records are transferred and colour plotting takes place in 2D or 3D graphics of the corrosion rates, the half-cell potentials and the electrical resistance, for documentation and reporting.

2.0 Instrument

Mainly two different types of instruments of their latest models such as the Galvapulse 5000, made in Germany and the GECOR 8, made in the USA, are widely used for the measurement of corrosion and the prediction of corrosion for the service life estimation of RC structures. All these instruments consist of software, a pulse generator, calibration units for the pulse generator, a measuring cell, a reinforcement locator, a reinforcement conductivity meter and other accessories.

The main features of such instruments are:

- Reliable evaluation of the reinforcement corrosion in anaerobic concrete environment.
- Lightweight, handheld equipment, easy-to-operate.
- Two operation modes, one for speedy measurement, using only half-cell potentials and electrical resistance (1–2 seconds per test), and another for corrosion rate, half-cell potentials and electrical resistance (5-10 seconds per test). The first mode is normally used to identify the anodic and the cathodic areas, while the second is used in anodic areas, where the corrosion rate is a decisive parameter to be measured.
- Testing on rough or curved surfaces.
- Storage capacity of up to 20,000 records in the handheld computer.

3.0 Applications

Reliably to measure the reinforcement corrosion for the following applications:

- Service life estimation
- Evaluating the efficiency of corrosion arresting measures such as application of inhibitors, membranes or electrochemical removal of chlorides
- Condition surveys of suspect reinforced structures,

especially structures in wet environment where the classic potential mapping may provide misleading and/or insufficient information
- Monitoring RC structures for corrosion activity
- Testing the corrosion activity in repaired areas

Corrosion activity was evaluated of a 20 years old bridge column with the GalvaPulse as shown in Figure 3.

Fig. 3: Corrosion monitoring of a heavily corroded column

The rate of corrosion measured on the circumference of the column for height of 200 cm from the ground level was plotted in Fig. 4 and the half cell potential of the same column was also plotted in Fig. 5.

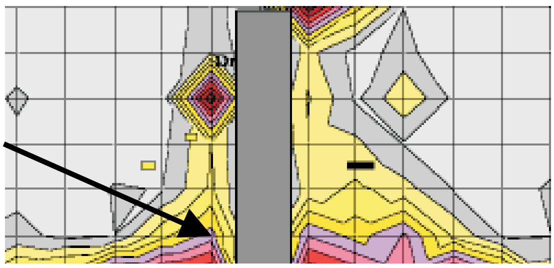

Fig. 4: Corrosion rate measurement of bridge column

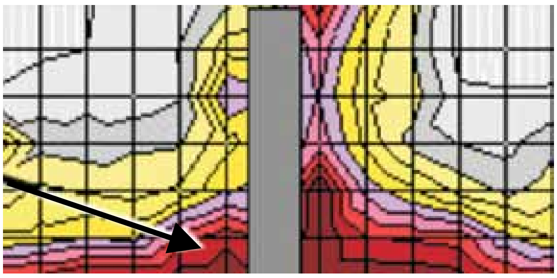

Fig. 5: Half-cell potential measurement

The different colours show the ranges of rate of corrosion and half cell potential respectively. At a particular point as shown in the above figures by arrow marks, the rate of corrosion was 210 to 230 µm per year and half cell potential was – 450 mV to – 500mV.

The fairly constant corrosion rates as measured over the past 20 years corresponds to a cross section loss of the reinforcement of 20 years times @ 0.22 mm per year would be 4.4 mm. This was also confirmed after opening at the same location of the column.

4.0 Calibration

Corrosion analyser equipment is having a calibration unit and a check block with a stainless steel and a corroding black steel bar embedded having known potential difference for calibration (Fig. 6).

Fig. 6: A check block for calibration of the equipment

5.0 Limitations

One difficulty with the Galvanostatic pulse transient technique is that the response to the pulse has to be 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 double layer capacitance. This technique, and those of AC impedance and harmonic analysis, suffers 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.

6.0 Accuracy and Variation

The half-cell potentials measured with the Ag/AgCl electrode is within ± 5 mV from a calibrated one. The electrical resistance variation is less than ± 5%. The precision of the corrosion can only be evaluated by comparison to actual weight loss measurement of the reinforcement subjected to long term corrosion conditions.

Available sensors A and B have detachable Ag/AgCl reference electrodes which reduces its maintenance. These are an alternative to the well-known and more extended $Cu/CuSO_4$ reference electrodes.

The values of corrosion currents measured by the GalvaPulse (5 sec. measurement duration) are significantly higher than those measured by the GECOR (100 sec. measurement duration), especially for the specimens with 0% Cl in which the steel bars should be in a passive state. It seems that the measurement duration plays an important role. The ohmic resistance measured by the GalvaPulse is the highest one probably due to its small size of sensor.

Understanding Rapid Chloride Permeability Test (RCPT) Method

[Excerpts from Technical Bulletin TB-0100 of GRACE, http://www.na.graceconstruction.com/custom/concrete/downloads/TB_0100B.pdf]

1.0 Fundamental Principles

The RCPT is an electrical test in which the test result is a direct function of the resistance of the test specimen. In principle, the use of electrical properties to measure the ionic transport properties of concrete is well grounded and is affected by two aspects of the concrete: (1) the connectivity of the capillary pore system, and (2) the electrolytic capacity (ionic concentration) of the pore solution. The capillary pore system is of primary interest, with respect to assessing the durability of concrete.

This test method was originally developed by the Portland Cement Association, under a research program by the Federal Highway Administration (FHWA). The original test method may be found in FHWA/RD-81/119, "Rapid Determination of the Chloride Permeability of Concrete." This test method was further modified and adapted by various agencies and standard's organizations such as:

- AASHTO T 277, "Standard Method of Test for Rapid Determination of the Chloride Permeability of Concrete"
- ASTM C 1202–97 (2008), "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration"

2.0 Method of Testing

This test is performed according to the procedure prescribed in ASTM C 1202 on specimens of 100 mm diameter and 50 mm thickness, which are obtained by slicing 100 x 200 mm cylinder specimens. On the testing day, the vertical curved surface of the specimens should be coated with epoxy paint, and avoid coating the flat test surfaces and covering any pinholes. The epoxy specimens should be allowed to dry for 18 to 24 hrs in a desiccator. After drying the specimens, they should be placed in a water bath which is stored inside a desiccator connected to a vacuum pump. The desiccator should be evacuated to between –75 and –80 kPa and this vacuum should be maintained for 3 hours ± 15 min. After 18 hrs of soaking, the specimen should be removed from the water. Then it should be placed in the test device between the two cells. The left cell (anode) is filled with a 3% NaCl solution and the right cell (cathode) is filled with 0.3N NaOH solution (Fig. 1).

This system is connected to a power source and a 60 V potential is applied along the specimen for 6 hours. At every 30 minute interval, the current is recorded using a multimeter. At the end of 6 hours, the specimen is removed from the set-up and the total charge passed (Coulombs) through the specimen is calculated.

Fig. 1: RCPT Apparatus

3.0 Interpretation of Test Results

The rapid chloride permeability test does not, however, directly measure the depth or rate of chloride penetration. This makes it difficult to directly correlate results from the test with a desired service life and has led to a significant amount of debate about the proper use and applicability of the test. It should also be noted that, in quality control and acceptance testing applications, ASTM C 1202 recommends the use of the qualitative terms as given in Table 1, rather than the numerical results of the test.

Table 1: Chloride permeability based on charge passed

Charge Passed (Coulombs)	Chloride Permeability	Typical of
> 4,000	High	High W/C ratio (> 0.60) conventional PCC
2,000 - 4,000	Moderate	Moderate W/C ratio (0.40 - 0.50) conventional PCC
1,000 - 2,000	Low	Moderate W/C ratio (0.40 - 0.50) conventional PCC
100 - 1,000	Very Low	Latex - modified concrete or internally - sealed concrete
< 100	Negligible	Polymer-impregnated concrete, Polymer concrete

The above chart was originally referenced in FHWA/RD-81/119 and is also used in AASHTO T 277-83 and ASTM C 1202 specifications. The test itself is not accurate enough to clearly define exact concrete permeability levels. Five categories were created in which coulomb test results from different test samples that fall in the same category were considered to be equivalent.

Even so, coulomb limits are given in many specifications, and a wide range of values have been used, one point that should be raised when considering test limits is that concrete mixtures containing fly ash or slag cement will often not reach their permeability potential until after curing for 56 days or more, so setting low 28-day coulomb limits can be problematic. For example, the Canadian standard CSA A 23.1-04 has set 56-day limits of 1500 coulombs for concrete exposed to freezing and chlorides and 1000 coulombs for high-performance concrete (HPC), where extended service life is required. Other agencies have effectively compensated for the effects of fly ash and slag cement by adopting higher limits at 28 days.

Care should be taken in interpreting of this test when it is used on surface-treated concretes, for example, concretes treated with penetrating sealers. The results from this test on such concretes indicate low resistance to chloride ion penetration, while 90-day ponding tests on companion slabs show a higher resistance.

For specimen's diameter higher than 95 mm, the value for total charge passed must be adjusted by multiplying factor and for specimens with diameters less than 95 mm, particular care must be taken in coating and mounting the specimens to ensure that the conductive solutions are able to contact the entire areas during the test.

It is important to understand that these ranges were established on laboratory concrete by the test method described above. The ranges should be used only for the purpose of comparison.

3.1 Comparison of RCPT with Rapid Migration Test

Rapid Migration Test (RMT) is carried out by incorporating certain changes in the AASHTO TP 64 procedure in order to utilize the same set-up of RCPT. It uses a voltage whose magnitude is varied based on the permeability of the concrete sample. Rather than using the total charge passed to gauge the permeability of concrete, this method allows direct measurement of the depth of chloride penetration. After completion of the 18-hour test, the specimen is splited and the exposed surface is sprayed with a 0.1N silver nitrate solution. The solution reacts with chloride ions and changes from grey to colourless, thus indicating penetration depth. The results are expressed in mm/V-hr by dividing the average chloride penetration depth by the product of the applied voltage and the duration of the test.

A comparison between RCPT and the rapid migration test values is given in Table 2. The test is meant only to give an indication as to how the concrete tested relates to the values in the chart or to other concrete being tested under the test procedure.

Table 2: Approximate correlation between rapid chloride permeability and rapid migration test results

Sl. No.	Rapid migration test value, mm/V hr	Rapid chloride ion permeability test value, Coulombs
i.	0.034	3000
ii.	0.024	2000
iii.	0.012	800

4.0 Factors Influencing RCPT Results

There are many factors that may affect the accuracy of the test procedure. The age and curing of the test specimen affects the results dramatically. In general, the older the specimen the lower is the coulombs, assuming that the sample has been cured properly. Research has also indicated that the presence in the concrete of admixtures, containing ionic salts, may affect the results obtained. The presence of ionic salts increases the amount of coulombs passed. It is theorized that the ionic salts act as an additional transport medium for the charge. This results in a higher coulomb level even though the concrete's permeability has not changed. Admixtures that contain ionic salts are primarily accelerators composed of materials such as Calcium Nitrite, Calcium Nitrate, Calcium Chloride and Sodium Thiocyanate. It is strongly recommended that if concrete containing these admixtures is to be tested using this method, tests be performed with and without the admixture to see what effect the admixture has on the results.

In such cases long-term chloride ponding tests are recommended which indicate the concretes with such admixtures are at least as resistant to chloride ion penetration as the control mixtures.

Since the test results are function of the electrical resistance of the specimen, the presence of reinforcing steel or other embedded electrically conductive materials may have a significant effect. The test is not valid for specimens containing reinforcing steel positioned longitudinally, that is providing a continuous electrical path between the two ends of the specimen.

The other factors which affect the test results are the cement factor, air content, water / cement ratio, curing of the test sample and aggregate source or type.

5.0 Accuracy

RCPT results correlate fairly well with chloride penetration by diffusion in which the pore system has the primary influence on results. Two notable exceptions where the ionic concentration of the pore solution greatly affects RCPT results occur with silica fume (very low) and Calcium Nitrite (very high). The increase in temperature during the test also causes increase in rate of charge passing. This test is further complicated by the fact that a number of mechanisms including migration, diffusion and permeation are at play here.

There has been a great deal of debate over this test method because of large variations in results on companion test specimens. AASHTO T277 states that the results of companion samples tested by the same operator should not vary by more than 19.5%. This is an extremely large variation in allowable results. The ASTM method shows that the results of two properly conducted tests by the same operator on concrete samples from the same batch may differ as much as 42%. On companion samples tested by different laboratories, this percentage is raised to 51%. This large variability in test results indicates the relative inaccuracy of the test method while maintaining that concrete samples which lie within this large acceptable range are essentially equal in quality.

6.0 Limitations

- RCPT has serious limitations while comparing mixes with different chemical composition since it is basically a conductivity test and can give misleading interpretation that chloride content of a mix with a high RCPT value has a proportionately high depth of chloride penetration when compared to a mix with a very low RCPT value.
- This test method does not replicate actual conditions that concrete would experience in the field. There is no condition where concrete is exposed to a 60-volt potential. To ensure high durability, electrical conductivity of less than 700 to 1000 Coulombs is often specified in practice, which is characterized as 'very low' as per ASTM rating. However, it is often seen that some types of conventional cement concrete, with a low water-to-cement ratio (0.3 to 0.4), cannot achieve the 700 to 1000 Coulombs. Yet, these same types of concrete exhibit negligible chloride penetrability when tested by the 90-day chloride solution pond test where no electric voltage is used to drive the chlorides into the concrete. Hence, this test would be applicable where correlations have been established between the RCPT and the long term chloride ponding test as described in ASHTO T 259.
- This test method does not measure concrete permeability. What it does measure is concrete resistivity. Resistance is calculated as volts divided by current. It has been shown that there is a fair correlation between concrete resistivity and concrete permeability.

7.0 Application

The RCPT data can be used only for preliminary assessment of chloride permeability, the conclusions drawn using RCPT have to be verified again by other tests on chloride penetration and micro-structural properties in this regard. To understand the advantages and disadvantages that affect the different tests on chloride ion penetration, a comparison is given in Table 3.

Table 3: Comparison of chloride penetration test methods

Test Method		A	B	C	Approximate Duration of Test Procedure
Long Term	AASHTO T259 (salt ponding)	Y	Y	Y	90 day after curing and conditioning
	Bulk Diffusion (Nordtest)	Y	Y	Y	40 - 120 days after curing and conditioning
Short Term	RCPT (T277)	N	N	N	6 hours
	Electrical Migration	Y	Y	N	Depends on voltage and Concrete
	Rapid Migration (CTH)	Y	Y	N	8 hours
	Resistivity	N	Y	N	30 Minutes
	Pressure Penetration	Y	Y	Y	Depends on pressure and concrete (but potentially long)
Other	Sorptivity - Lab	N	Y	Y	1 week including conditioning
	Sorptivity - Field	N	Y	Y	30 minutes
	Propan-2-ol Counter diffusion	N	Y	Y	14 days with thin paste samples
	Gas Diffusion	N	Y	Y	2-3 hrs.

Note: A : Considers chloride ion movement
B : At a constant temperature
C : Unaffected by conductors in the concrete
Y : Yes, N: No

8.0 Conclusion

The transport of chloride ions into concrete is a complicated and multi-mechanistic phenomenon. It is important to understand some of the basic concepts underlying chloride ingress into concrete to enable the proper consideration of this eventuality when designing structures in extreme environments with reinforced concrete.

At the present time this is the only test method that is widely accepted by the concrete industry. As more and more experience is gained with this test, as well as with other test methods, new procedures may be developed that measure concrete permeability more accurately.

Corrosion Assessment of Rebar – A Case study

[Excerpts from CECR, Vol. 22, December 2009,pp 38 - 43 by Radhikesh P. Nanda et.al, KIIT University, Bhubaneswar]

1.0 Introduction

In this case study a RCC hospital building at Cuttack, Orissa was taken for corrosion assessment and methods adopted for repairing. The assessment was divided into two parts:

- Visual inspection
- Detailed investigation by NDT method

A systematic visual inspection was conducted to get a fair idea about the deterioration and distress of the existing RCC buildings. Visual inspection and extensive photography of the building were taken to decide the extent of investigation and selection of tests. It was observed that columns and stair case beam of the building were cracked. Water soaking marks were present. Plaster and some concretes were worn-out from the column and stair case beam. Reinforcement bars were exposed. Fig. 1 shows the visual inspection showing rebar corrosion and spalling of concrete.

Fig. 1: Corrosion of rebar

Visual investigation was the obvious limitation that only visible surface can be investigated. Internal defects go unnoticed and no quantitative information could be obtained about the reinforcement. For these reasons, a visual inspection was supplemented by detailed investigation. Rebar corrosion was investigated by digital covermeter and corrosion analyzer.

2.0 Digital Covermeter (Profometer)

A covermeter or profometer was used for measuring concrete cover. By means of this test it was able to detect rebar size, direction and position. Measurements were based on the damping of a parallel resonant circuit. After preparation of surface the instrument was made ready for testing. The search head touched to the point of testing and was moved slowly. An electromagnetic field was generated by the search head (probe). When a reinforcing bar or other metal object lied within this field, the line of forces were distorted. The disturbance caused by the presence of the metal in turn produced a local change in field strength detected by the search head (probe) and indicated by the meter reading. It was therefore possible to locate the reinforcing bars and determine their orientation. Cover to bar was also determined by a suitable calibration for the particular size of the bar and the material under investigation. For the above purpose the profometer-5 (rebar locator) was used. Fig. 2 shows testing with cover meter.

Table 1 shows the data obtained from rebar locator. It was found from the above calibrations that average cover thickness was 32 mm and the average bars were 15 nos. in X-axis in 1.5 m and 3 nos. in Y-axis in 0.5 m.

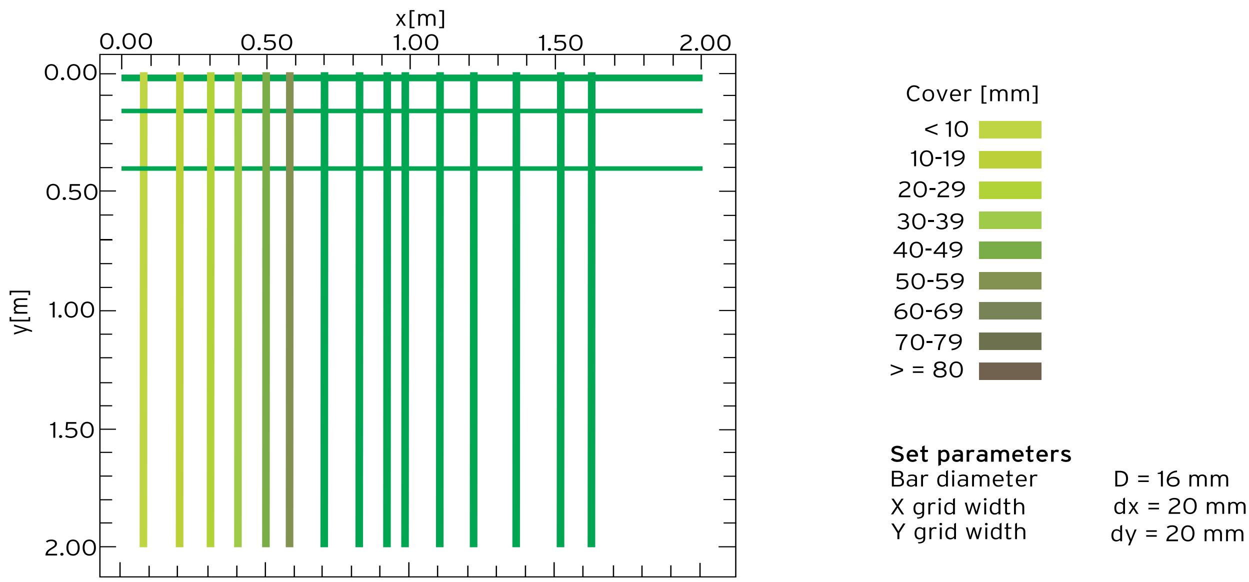

Fig. 2: Data obtained from rebar locator

Table 1: Statistical data from rebar locator

Measured covers

x [m]	Cover [mm]
0.08	34
0.20	35
0.30	35
0.40	32
0.50	30
0.58	27
0.70	28
0.82	33
0.92	29
0.98	28
1.10	29
1.22	32
1.36	34
1.52	26
1.62	69

y [m]	Cover [mm]
0.02	36
0.16	46
0.40	40

Statistic

I Number of measured bars
ii Average measured cover
iii Standard deviation
iv Maximum of measured covers
v Minimum of measured covers
vi Span

			x	y	
i	N	=	15	3	
ii	m	=	33.4	40.7	mm
iii	sa	=	10.3	5.0	mm
iv	Max	=	69	46	mm
v	Min	=	26	36	mm
vi	R	=	43	10	mm

3.0 Corrosion Analysing Instruments

The potential of a corroding rebar differs from that of a non-corroding rebar by about several 100mv. The fact was utilized in the potential measurement to provide information about the condition of the reinforcement. After surface preparation the instrument was made ready for the testing. The following were the requirements for testing.

- Connection to the reinforcement (non-corroding).
- Reference electrode (copper or copper sulphate electrode was recommended).
- Voltmeter (possibly with memory and possibility of printing option).

Fig. 3 shows different points of testing by corrosion analyser and the pictures obtained from the analyser. From the calibration it was found that the green shaded portion whose potential was highest was more corroded (65.5% to 99.3%).

4.0 Conclusions

Reinforcement concrete structures have the potential to be very durable and capable of withstanding a variety of adverse conditions. However, failures in the structures do still occur as a result of premature reinforcement corrosion. Corrosion of reinforcing steel which was main cause of the deterioration was easily identified visually by characteristic cracking pattern parallel to the reinforcement, spalling of the concrete cover. From detailed NDT investigation by cover meter/ rebar locator it was found that average cover thickness was 32 mm and at some places cover was less than 25 mm which required some additional cover. From corrosion analyzer the area could be marked exactly where potential was higher to carry out the repair and rehabilitation.

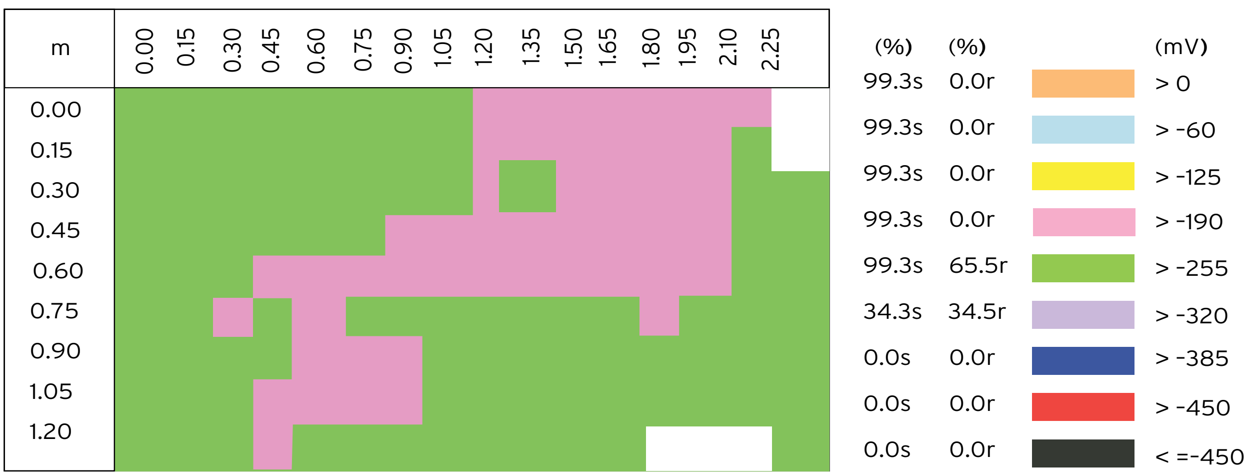

Fig. 3: Pictures from corrosion analyser

Programmes Conducted

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Protection Measures against Weathering Distresses in Concrete Structures

Date : 15 July 2011

Participants: Orbit Corporation Limited, Dreams Unlimited, Himesh Decor, Royal Waterproofing, Super House Construction etc.

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Date : 16 to 26 August 2011

Structural Diagnosis and Repair of Concrete Structures

Date : 29 to 30 September 2011

Participants: ITD Cementation India Ltd., Orbit Corp. Ltd., Mott McDonald, Mumbai Port Trust, Adani Infra. Ltd., Painterior India Ltd., Gherzi Bostern Ltd. etc.

Participants and Faculties in Structural Diagnosis and Repair of Concrete Structures training programme

• External Training Programmes

Entrepreneurship in Waterproofing and Repair of Concrete Structures

Date : 9 & 10 August 2011

Venue : C.B.Kora Training Institute of Khadi & Village Industries Commission (KVIC), Borivali, Mumbai

Waterproofing of Roofs and External Walls (Two Batches)

Date : 6 & 19 August 2011

Venue : The Institution of Engineers, Mahalaxmi, Mumbai

Participants : MHADA, Hirco, Construma Consultant, Soham Builders, NALCO (Bhubaneshwar), Essar Projects, Indian Oil Corp, DCM Shriram Consolidated (Kota), Ramboll Engg. Consultancy Services, Raheja Corp - Inorbit Mall (Pune), Shriram Fertilizers & Chemicals (Kota), Essar Engg. Services, Satellite Developers etc.

Participants and Faculties in The Institution of Engineers, Mahalaxmi, Mumbai training programme

Waterproofing Materials and Technologies

Date : 21 – 24 September 2011

Participants : Engineers of Rural Works Department, Govt. of Orissa.
Venue : Office of Chief Engineer, Rural works, Bhubaneshwar
Organiser : Engineering Staff College of India, Hyderabad

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• Paper Presentation

Mr. S. C. Pattanaik presented a paper on **"Causes, Evaluation and Repair of Cracks in Concrete Structures"** in the seminar on "Recent advances in Civil Engineering" at Institution of Engineers, Bhubaneswar on 16 – 17 July 2011.

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2	26 to 30 Dec 2011	Department of Civil Engineering, Institute of Technology, Nirma University, Ahmedabad, Gujarat	Diagnosis, Repair and Protection of Concrete Structures	₹ 2000 for Faculty members ₹ 4000 for Professional Engineers	• Construction Failures • Distress in Concrete Structures • Condition Survey • Diagnosis and Damage Assessment by Various NDT Techniques • Cracks in Concrete Structures • Repair Materials • Repair and Retrofitting Techniques and Methodologies • Waterproofing Materials, systems and Applications • Maintenance of Structures
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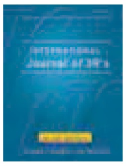

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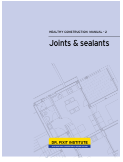

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