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Cement & Concrete Composites 24 (2002) 27–34

Cement & Concrete Composites

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The use of permanent corrosion monitoring in new and existing reinforced concrete structures

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Abstract

Corrosion monitoring systems consisting of linear polarisation, concrete resistivity and other probes have been installed in new structures to monitor durability and in existing structures to evaluate rehabilitation strategies such as corrosion inhibitor application and patch repairs. The types of sensors used, data collection techniques, results and interpretation are discussed. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Corrosion in concrete; Linear polarisation; Corrosion rate; Deterioration rate; Durability; Chloride attack

1. Introduction

Many reinforced concrete structures have given excellent service with minimal maintenance. However, as the infrastructure has aged it has become apparent that some environments were more severe than originally thought, and some construction and design problems have led to lower service lives and higher maintenance costs than originally envisaged. The worst of these problems is caused by corrosion of steel in concrete, either due to carbonation or chloride attack.

One of the latest estimates from the USA [1] is that the cost of damage due to deicing salts alone is between \$325 and \$1000 million per year to bridges and car parks. In the UK the Department of Transport estimates a total repair cost of £616.5 million due to corrosion damage to motorway bridges [2]. These bridges represent about 10% of the total bridge inventory in the UK. The total problem may therefore be ten times the DoT estimate. There are similar statistics for Europe and particularly the Middle East. Deterioration occurs on buildings and other structures as well as bridges.

This paper looks at how permanently embedded corrosion monitoring devices can be used to monitor the development of corrosion problems on a new or existing reinforced concrete structure before embarking on repair or rehabilitation of the structure.

There are many devices for investigating corrosion problems. This is because there is no single technique which will tell the engineer what he needs to know, that is how much damage there is on the structure now and how rapidly the damage will grow with time. Corrosion monitoring, when used in association with "snapshot" surveys can give a more complete picture of the changing condition of a structure in time as well as in the three physical dimensions of the structure.

2. Corrosion monitoring

The technique of conducting a condition survey on reinforced concrete structures suffering from corrosion of the reinforcement is now well documented [3,4] and there are a number of techniques that can be used to carry out such an assessment. Table 1 is a summary of the more widely used techniques.

All of these techniques can be used in isolation or combination to provide a "snapshot" of the condition of a structure. However, if we are interested in the rate of deterioration of the structure, it is useful to monitor the condition change with time. This is now being done on new structures with long lifetime requirements and older structures when corrosion damage has been found and repair is being deferred to cost, logistical or other reasons.

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PII: S0958-9465(01)00024-5

Table 1
Techniques for corrosion assessment of reinforced concrete

Method	Detects	User	Approximate speed
Visual	Surface defects	General	1 $m^2\ s^{-1}$
Hammer/chain	Delaminations	General	0.1 $m^2\ s^{-1}$
Cover meter	Rebar depth (& size)	General	1 Reading in 5 min
Phenolphthalein	Carbonation depth	General	1 Reading in 5 min
Chloride content	Chloride induced corrosion	General + lab	1 Reading in 5 min plus lab/site analysis
Permeability etc.	Diffusion rate	Corer + specialist	Core + lab
Impact/ultrasonics	Defects/Concrete quality	Specialist	1 Reading in 2 min.
Petrography	Concrete properties	Corer + specialist	Core + lab
Half cell[a]	Corrosion risk	General/specialist	1 Reading in 5 s
Linear polarisation[a]	Corrosion rate	Specialist	1 Reading in 5–30 min
Resistivity[a]	Concrete resistivity	General/specialist	1 Reading in 20 s

[a] These techniques are suited to permanent corrosion monitoring.

2.1. Half cell potentials

The principles and practice of half cell potential measurement and interpretation are explained elsewhere [3,5–7]. It is now common practice to conduct a half cell potential survey of reinforced concrete structures known, or believed to be suffering from corrosion, particularly due to chloride contamination. It is also normal practice to embed "permanent" half cells in concrete to monitor the performance of cathodic protection systems for atmospherically exposed steel in concrete. Many thousands of embeddable half cells have been installed in this way.

It is not economic to install half cells all over a structure to monitor its changing corrosion condition. However, either during construction or after a condition survey, vulnerable and representative locations can be determined and corrosion monitoring installed. A half cell is a vital part of the corrosion monitoring system.

However, on very long life structures the use of normal embeddable half cells may not be possible throughout the life of the structure without replacement or installation of an alternative "pseudo reference" electrode. This is because most half cells have a life of one or two decades whereas some structures have lives in excess of a century. Graphite, stainless steel, lead, mixed metal oxide or other pseudo references can be used. However, these alternatives are less stable in the short and the long term as the interface that produces the electrochemical reaction against which the steel/concrete interface potential is measured is exposed to changes in the environment itself and will therefore be affected by changes in moisture, oxygen, chloride level and pH more directly than a "true" reference half cell as illustrated in Fig. 1.

The half cell potential measurement gives an indication of the corrosion risk of the steel. The measurement is linked by empirical comparisons to the probability of corrosion.

Standard electrode theory tells us that the potential of a reversible cell consisting of copper in copper sulphate and iron in ferrous chloride is:

$$E = E^{\circ} - \frac{RT}{2F} \ln \frac{\{a(\mathrm{Fe}^{2+})\}}{\{a(\mathrm{Cu}^{2+})\}}.$$

Since all the terms are constant other than the activity of Fe^{2+}, the potential is a function of the activity (approximately the concentration) of the iron in solution. This assumes that the cell is reversible and that the iron forms ferrous chloride. The activity of $FeCl_2$ surrounding the reinforcement is obviously linked to the corrosion of the steel but it is not a direct function of the corrosion rate. Also this assumes full reversibility of the reaction. Although the reaction:

$$\mathrm{Fe} + 2\mathrm{Cl}^- \leftrightarrow \mathrm{FeCl}_2 + 2\mathrm{e}^-$$

is reversible, the subsequent reactions creating rust are not.

2.2. Linear polarisation measurements

Linear polarisation is simple in principle although the underlying theory is complex and its use in practice is also complex. The theory of linear polarisation, also known as polarisation resistance, relies on the relationship between the half cell potential of a piece of corroding steel and an external current applied to it, i.e., the corrosion rate is proportional to the applied current divided by the potential shift. This can be expressed by the equations:

$$I_{\mathrm{corr}} = \frac{B}{R_{\mathrm{p}}},$$

where I_{corr} is the corrosion current, B is a constant related to the anodic and cathodic Tafel slopes and R_{p}, the polarisation resistance = $\mathrm{d}E/\mathrm{d}I$, where $\mathrm{d}I$ is the change in current $\mathrm{d}E$ is the change in potential.

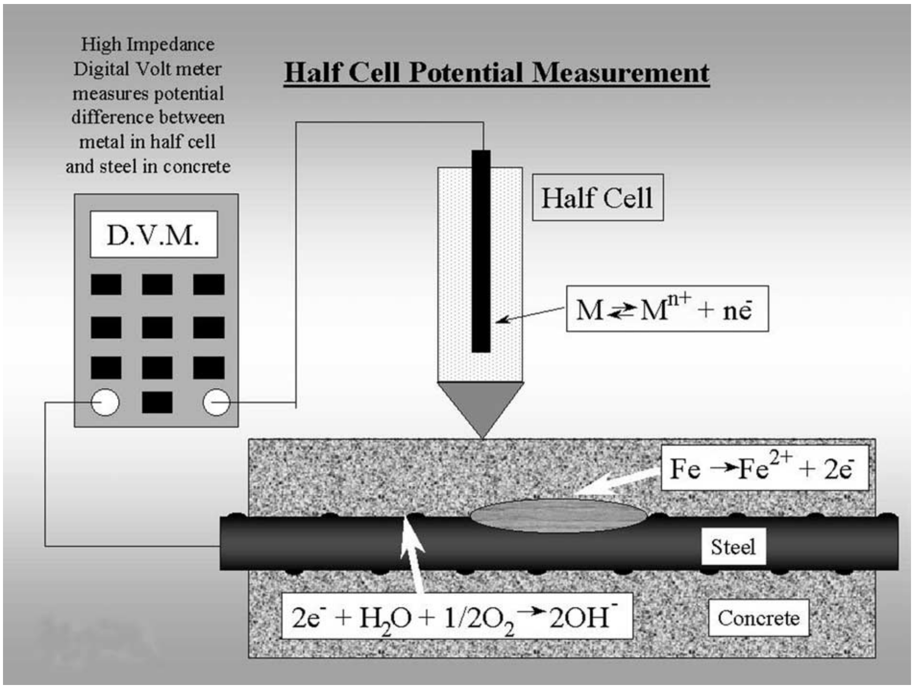

Fig. 1. Half cell potential measurement.

Linear polarisation (LP) is usually conducted in aqueous solutions on small, uniformly corroding specimens. A number of LP devices are now available for steel in concrete. One of the most sophisticated is illustrated in Fig. 2.

The system consists of a half cell to measure the potential and its change, an auxiliary electrode to pass the current and, in this case, a guard ring around the auxiliary electrode to constrain the electric field from the auxiliary electrode because of the size of the corroding

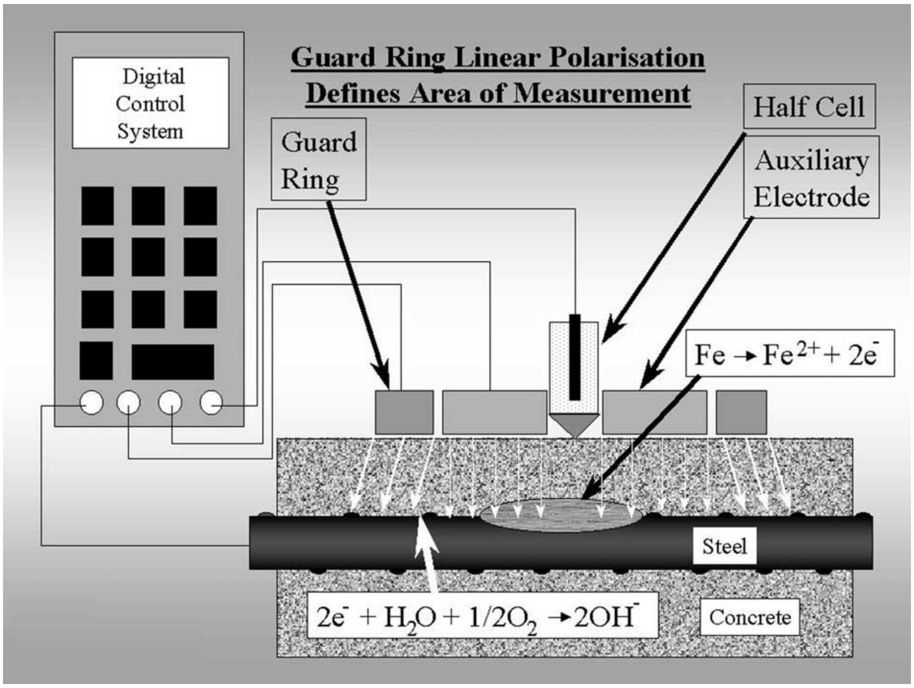

Fig. 2. Guard ring linear polarisation defines area of measurement.

rebar. This ensured that a measurement is taken from a defined area of steel and prevents gross errors in the area of measurement [3,8].

If linear polarisation is used in corrosion monitoring then in 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 macrocell effects may be different if the electrode is left unconnected to the steel between readings. The system shown in Fig. 3 has been designed to fit into the rebar cage. A cable runs from the unit to a multipin socket fixed to the formwork. After casting and curing the concrete, the formwork is removed, leaving the socket exposed for connection to a hand held or permanently wired monitoring system.

In existing structures corrosion monitoring can be retro-fitted by drilling, coring or excavating the concrete and installing half cells and auxiliary electrodes. Isolating a piece of rebar enables us to have a controlled measurement area without resorting to guard rings or separately embedded working electrodes. This way the corrosion measurement is on a representative piece of bar in an undisturbed environment as shown in Fig. 4.

2.3. Macrocell current measurements

In new construction, a macrocell current device can be set up using a configuration similar to Fig. 3 but with a series of mild steel working electrodes and a stainless steel cathode where the half cell is shown in Fig. 3. This is fixed in the formwork on new construction with the first working electrode resting on the form with minimal cover, and the last at rebar depth. As each working electrode depassivates with incoming chlorides (or carbonation), there is a step up in the current flow between the depassivated working electrode as it becomes an anode, and the stainless steel cathode. The system will then measure the increasing current flow as the macrocell current increases due to increased depassivation and/or higher corrosion rates as the carbonation front advances and/or the chloride level increases at the electrode.

2.4. Concrete resistance and resistivity measurements

Two or four pin probes can be embedded in the concrete at different depths to monitor moisture movement and permanent changes which may be associated with chloride ingress. These can be sets of pins or a series of "washers" separated by insulating cylinders.

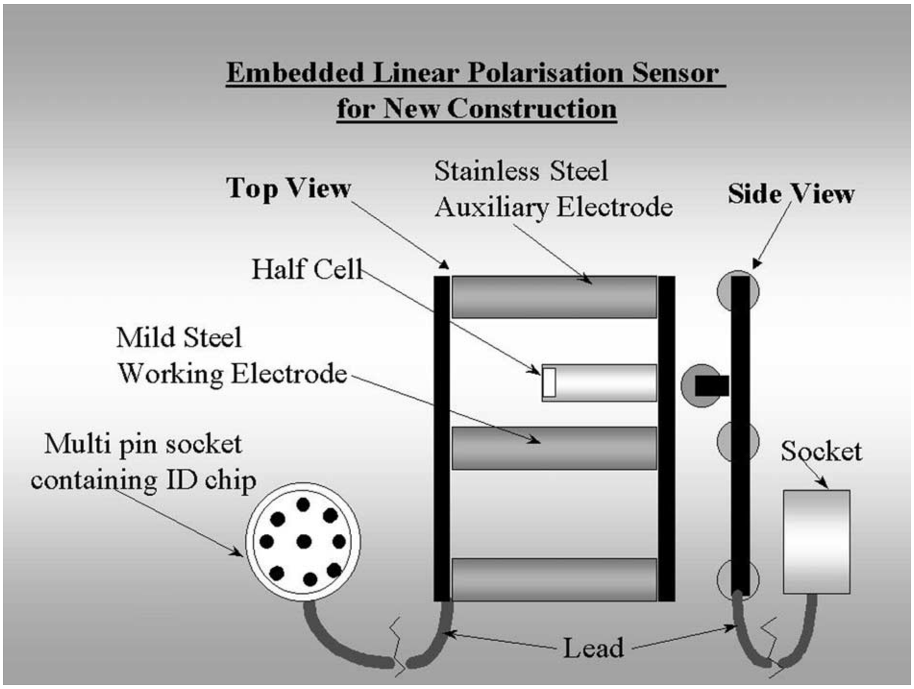

Fig. 3. Embedded linear polarisation sensor for new construction.

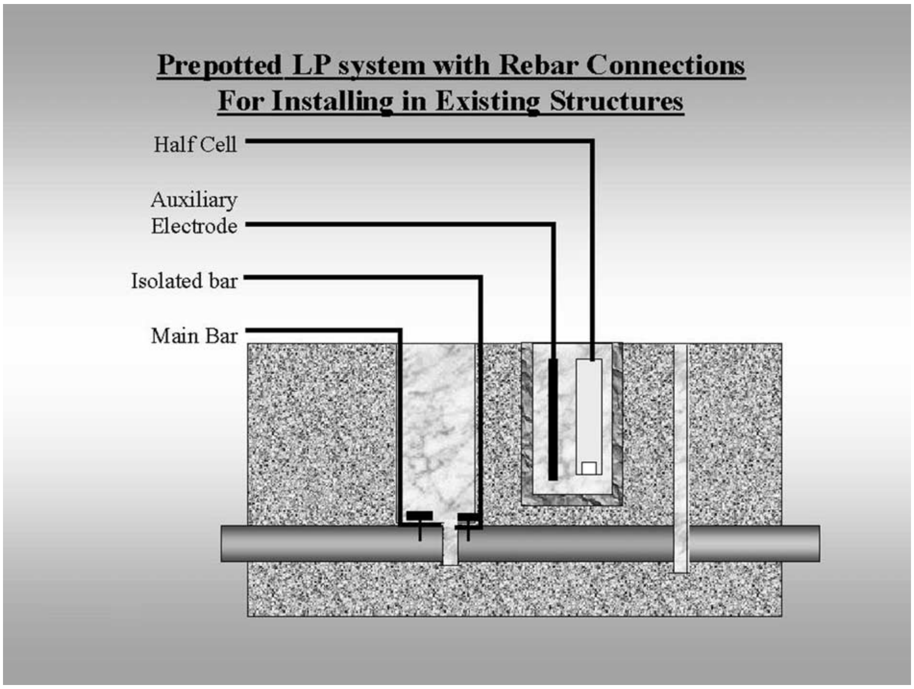

Fig. 4. Prepotted linear polarisation system with rebar connections for installing in existing structures.

2.5. Other measurements

It is common practice to include a temperature sensor in the assembly. Chloride and pH sensitive electrodes, as well as relative humidity probes have been used in some installations. However, the stability of the sensors is difficult to guarantee over a period of years, and recalibration is almost impossible.

3. Applications and results

The authors have applied corrosion monitoring to seven structures in the past two years. These have included car parks, power station plant, wharves, and highway structures. In one case corrosion inhibitors have been applied to reduce corrosion and the corrosion monitoring system is being used to monitor the effectiveness of the treatment and to produce recommendations for further inhibitor treatment or other repair.

3.1. Installation on new construction

The authors have installed a series of over 30 sensors into precast deck elements for installation in a road tunnel. Sensors were predominantly LP with temperature sensors and an identity chip in the socket so that a microprocessor control and data logging system can identify the location as it takes measurements and downloads the data. A series of four probe resistivity sensors were also installed along with a few macrocell probes.

Preliminary data shortly after installation of the deck slabs in the tunnel showed that as the concrete continued to dry out. The concrete resistivity increased, the half cell potentials moved more positive and the corrosion rates decreased as full passivation was established.

3.2. Installation of monitoring probes in a 17 year old jetty

The structure is a reinforced concrete coal loading jetty for Kingsnorth power station on the Medway Estuary East of London. It is used for receiving coal at the station and potentially for importing coal for power stations throughout the UK.

The facility management requires a five year maintenance horizon, which makes sophisticated, long term repair, such as cathodic protection, uneconomic. Therefore a low level programme of concrete repair has been underway on a seasonal basis since 1993 when chloride induced corrosion first led to extensive cracking and spalling on the longitudinal and lateral beams supporting the jetty deck in the splash and tidal zones.

As part of a research programme and to evaluate the effectiveness of the repairs, corrosion monitoring was installed in representative areas of the structure. The aim was to see how effective the repairs were in eliminating corrosion, and whether patch repairs lead to the "incipient anode" effect where removing the anodic area by repair removes the sacrificial anode effect that has been protecting adjacent steel, leading to the breakout of corrosion around the repair.

Probe locations were as follows where beam numbering starts at the shore:

1. On transverse beam number 21 adjacent to shotcrete repair on soffit of beam.
2. Ditto, higher up vertical face.
3. On longitudinal beam in between 21 and 22, partially in shotcrete repair.
4. Ditto in parent concrete adjacent to shotcrete repair.
5. On transverse beam 7 in repair shotcrete.
6. Ditto in parent concrete adjacent to shotcrete repair.
7. On longitudinal beam between transverse beams 7 and 8 in repair shotcrete.
8. Ditto in parent concrete adjacent to shotcrete repair.

Both beams 7 and beam 21 are in the tidal zone and are fully exposed at low tide. The corrosion damage reduces beyond beam 21. Probes were installed at the end of a programme of concrete repair, where bars had been exposed and shotcrete applied to restore the cover and replace chloride contaminated concrete.

In all cases the probes were located on the eastern side of the jetty, away from the power cables and fuel lines running along the west side, and giving reasonably short (less than 10 m) cable runs from the probes to the deck. There were two separate termination boxes, one for the probes around beam 21 and one for those around beam 7. Boxes were mounted on the end of the beam at deck kerb level by the railing.

The eight test sites comprise the following:

- Stainless steel auxiliary electrode to perform linear polarisation (LP) measurements;
- electrical connections to the rebar cage;
- electrical connection to rebar;
- permanently embedded silver/silver chloride/potassium chloride half cell for potential and LP measurements;
- temperature sensor;
- 4-pin stainless steel electrical resistivity probe;
- extra connection to isolated section of steel (except location 5) to allow linear polarisation on a piece of steel of known area.

This enables us to carry out the following measurements:

- Half cell (corrosion potential) tests on isolated (known area of measurement) and main rebar;
- linear polarisation (corrosion rate) measurements on isolated and main rebar;
- electrical resistivity of the concrete;
- temperature within the concrete.

The probes were installed in 1997 and data are being collected manually using hand held, visual output meters, with reports to the client. The first four sets of data are shown in Table 2. Probes are generally performing well, although occasionally it is not possible to get readings, possibly due to local drying out or drift in potentials. However, most results are stable and reflect the corrosion condition of the repaired and unrepaired areas where probes are installed.

Measurements were taken twice in October 1997, January and October 1998 and February and November 1999. Most half cell potentials have declined with time showing a degree of settling down. The exception is location 6 which is showing the most active (negative) potential. The temperature varies with the seasons. Concrete resistivity is very variable with location, probably due to both differential wetting with tides and splash and differences between repair and original concrete. Resistivity levels are very high in locations 1, 2, 4 and 7. This may be due to a very dry environment around the probes or problems with embedment. The embedment technique has been improved in subsequent installations. There was an initial reduction in corrosion rates, which may be a function of initial steel passivation or drying out, particularly in repair areas. Despite minimising the disturbance to the steel being measured as discussed above, there is always a degree of "settling down" after installation. Location 2 has the highest corrosion rate consistently, although it is generally declining like most of the others. Monitoring over a long period on other structures has shown that while there are cyclical changes due to tides as well as seasons, it is necessary to monitor over several years to evaluate the long term trends and day to day fluctuations can be misleading.

The areas used to calculate corrosion rates from I_{corr} values (rate isolated in Table 2) was a direct calculation of area for isolated rebars based on length and diameter of the isolated bar section. For the continuous rebar measurement (rate continuous in Table 2) the area was based on the first three readings giving a comparable corrosion rate to the isolated rebar.

Future measurements will determine whether time or temperature has the greatest effect on the corrosion rate. So far there is no significant difference between measurements in the shotcrete repairs or the unrepaired concrete, nor between measurements on disconnected section of steel (as in Fig. 4) or the rest of the steel. Corrosion rates vary from a high of 67 micrometers section loss per year on Beam 21 TP 2, dropping to about half that in the most recent readings, to less than 10 microns per year in the beam 7 repair (TP7).

4. Conclusions

1. The development of durable, embeddable sensors and inexpensive microprocessor control and communica-

Table 2
Corrosion monitoring data from kingsnorth power station jetty

Date	8/10/97	30/10/97	27/1/98	20/10/98	1/2/99	10/11/99
Time	12:00	12:00	10:00	12:00	10:00	11:00
Run time [days]	0	22	111	377	481	763
*TP*1 – *Transverse* 21 *lower*						
E_{corr} isolated [mV Ag/AgCl]	−357.0	−337.0	−327.0	−350.0	−329.0	−154.0
Rate isolated [um/y]	29.7	23.5	18.2	26.6	20.3	24.2
E_{corr} continuous [mV Ag/AgCl]	−373.0	−354.0	−364.0	−371.0	−374.0	−207.0
Rate continuous [um/y]	29.1	22.5	19.9	25.3	22.5	28.4
Resistivity [ohm cm]	7.5E + 03	6.3E + 04	9.1E + 04	3.1E + 04	5.0E + 04	7.4E + 04
Temperature [°C]	17.3	9.6	4.8	12.1	0.3	13.7
*TP*2 – *Transverse* 21 *upper*						
E_{corr} isolated [mV Ag/AgCl]	−395.0	−368.0	−386.0	−415.0	−375.0	−348.0
Rate isolated [um/y]	67.4	45.7	39.2	50.8	36.8	37.7
E_{corr} continuous [mV Ag/AgCl]	−363.0	−344.0	−354.0	−366.0	−346.0	−326.0
Rate continuous [um/y]	66.9	46.9	38.9	50.3	37.8	42.1
Resistivity [ohm cm]		3.9E + 04	3.6E + 04	3.1E + 04	5.2E + 04	6.8E + 04
Temperature [°C]	17.1	8.1	4.2	12.1	0.2	12.5
*TP*3 – *Longitudinal lower* (*repair*) between 21 *and* 22						
E_{corr} isolated [mV Ag/AgCl]	−352.0	−323.0	−324.0	−329.0	−297.0	−275.0
Rate isolated [um/y]	41.4	27.0	23.6	30.5	24.0	25.1
E_{corr} continuous [mV Ag/AgCl]	−306.0	−279.0	−280.0	−273.0	−288.0	−244.0
Rate continuous [um/y]	38.5	25.7	23.1	30.5	31.2	30.9
Resistivity [ohm cm]		5.0E + 05	1.1E + 06	3.1E + 05	6.8E + 05	1.9E + 06
Temperature [°C]	17.0	6.2	3.6	12.1	0.1	12.6
*TP*4 – *Longitudinal upper between* 21 *and* 22						
E_{corr} isolated [mV Ag/AgCl]	−418.0	−409.0	−432.0	−415.0	−431.0	−345.0
Rate isolated [um/y]	23.4	14.4	13.6	15.4	14.0	11.6
E_{corr} continuous [mV Ag/AgCl]	−342.0	−321.0	−334.0	−324.0	−326.0	−292.0
Rate continuous [um/y]	20.9	18.6	17.4	14.3	11.5	12.7
Resistivity [ohm cm]	1.9E + 04	1.2E + 05	1.6E + 05	3.1E + 05	2.0E + 05	3.3E + 05
Temperature [°C]	17.3	6.6	3.9	12.1	0.1	12.7
*TP*5 – *Transverse* 7 *lower* (*repair*)						
E_{corr} continuous [mV Ag/AgCl]	−520.0	−498.0	−511.0	−527.0	−528.0	−233.0
Rate continuous [um/y]				9.7	10.0	11.1
Resistivity [ohm cm]	7.9E + 02	3.9E + 03	4.4E + 03	3.8E + 03	2.4E + 03	1.4E + 04
Temperature [°C]	16.8	9.7	3.8	12.1	0.6	21.8
*TP*6 – *Transverse* 7 *upper*						
E_{corr} isolated [mV Ag/AgCl]	−338.0	−390.0	−453.0	−502.0	−469.0	−485.0
Rate isolated [um/y]	8.3	7.3	7.3	13.9	8.1	8.5
E_{corr} continuous [mV Ag/AgCl]	−362.0	−374.0	−419.0	−425.0	−469.0	−418.0
Rate continuous [um/y]	10.9	8.9	8.9	11.0	7.5	9.8
Resistivity [ohm cm]	3.9E + 03	3.9E + 03	3.9E + 03	3.8E + 03	5.0E + 03	
Temperature [°C]	16.6	7.9	3.7	12.1	0.7	25.1
*TP*7 – *Longitudinal lower* (*repair*) *between* 7 *and* 8						
E_{corr} isolated [mV Ag/AgCl]	−334.0	−308.0	−293.0	−225.0	−234.0	−195.0
Rate isolated [um/y]	11.5	8.3	6.1	2.2	2.0	10.7
E_{corr} continuous [mV Ag/AgCl]	−331.0	−291.0	−278.0	−198.0	−204.0	−175.0
Rate continuous [um/y]	9.9	6.1	11.4	2.6	4.0	10.2
Resistivity [ohm cm]	1.0E + 05	7.5E + 05		1.7E + 06		4.7E + 06
Temperature [°C]	17.8	6.3	4.0	12.1	0.8	13.3
*TP*8 – *Longitudinal upper between* 7 *and* 8						
E_{corr} isolated [mV Ag/AgCl]	−373.0	−287.0	−319.0	−282.0	−295.0	−298.0
Rate isolated [um/y]	45.2	21.4	12.8	17.7	13.3	14.1
E_{corr} continuous [mV Ag/AgCl]	−367.0	−285.0	−300.0	−283.0	−298.0	−293.0
Rate continuous [um/y]	21.7	11.0	11.9	17.8	14.2	15.9
Resistivity [ohm cm]	6.4E + 03	1.1E + 04	8.2E + 03	8.5E + 03	9.7E + 03	9.0E + 03
Temperature [°C]	17.6	7.2	4.3	12.1	0.8	15.3

tions, have encouraged the development of corrosion monitoring systems for new and existing reinforced concrete structures.

2. 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.
3. Installations have been carried out on new structures with long life requirements for planned maintenance and to prevent premature repair requirements
4. It is 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.
5. Monitoring systems can consist of sensors to measure the corrosion rate and concrete condition.
6. Results from systems installed over the past two years show changes as the concrete cures and dries out in new structures, and that it takes several months for the sensors to show passive, low corrosion conditions after construction or repair.

Acknowledgements

The authors would like to acknowledge the permission of National Power to publish their data and the help of Andrew Weatherley of Powertech who made the project possible.

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