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# Developments in Intelligent Monitoring of Concrete Structures

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# DEVELOPMENTS IN INTELLIGENT MONITORING OF CONCRETE STRUCTURES

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## INTRODUCTION AND BACKGROUND

Deterioration in concrete comprises an initiation period and a propagation period. The initiation period is characterised by changes that occur within the concrete in response to the exposure environment and continues until a stage is reached when damage begins to propagate. The propagation period begins at a point in time defined when a particular event occurs (e.g. loss of steel passivity due to chloride ingress) and continues until a specified limit state is reached. The initiation and propagation stages of a deterioration process result from a complex interaction of physical, chemical and electrochemical phenomena. Prediction of the field performance of reinforced concrete thus requires numerous data inputs, in particular, the response of the cover-zone concrete (covercrete) to the changing ambient environment in the vicinity of a specific structural element or part of a structure.

The performance of the surface zone is acknowledged as a major factor governing the rate of degradation of concrete structures since it provides the only barrier to the aggressive agents that initiate corrosion of the reinforcement. Cover-zone moisture state (which dictates transport processes); property variations within the cover zone and temporal changes in cover-zone properties all influence reinforced concrete durability. In-situ monitoring of cover-zone concrete is an absolute necessity in attempting to make realistic predictions as to the in-service performance of the structure with regard to likely deterioration rates for a particular exposure condition, compliance with the specified design life and as an early warning indicator of incipient problems.

The major part of the European infrastructure has reached an age where capital costs have decreased, but inspection and maintenance costs have grown to such an extent that they now constitute a major part of the recurrent costs of the infrastructure. Traffic delay costs due to inspection and maintenance programmes are already estimated to be between 15%-40% of the construction costs [FORCE Institute

(Denmark) Newsletter, 2000]. 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 repair options and scheduling of inspection and maintenance programmes, thereby minimising traffic delays resulting from road closures. The ability to continuously monitor cover-zone concrete (covercrete) – in real time - could also allow a more informed assessment of the current and future performance of the cover-zone. The development of sensor systems to assess covercrete performance and durability forms one important component of an overall integrated monitoring system.

It is now recognised that in the total management of structures, involving both whole-life economics and life-cycle calculations [Doran, D., 1996; British Standards Institution, 2000], integrated monitoring systems and procedures have an important role to play [Schieβl and Raupach, 2000]. When data from monitoring systems are used with improved service-life prediction models [European Union – Brite Euram III, 1998; European Union – Brite Euram III, 1999] additional savings in life cycle costs could result. Satisfactory guidelines for concrete durability can only be developed by monitoring covercrete performance under a range of exposure conditions, over an extended period of time. Indeed, performance-based specifications for concrete are now defined in EN 206-1: 2000 (Annex J) [European Committee for Standardisation, 2000] and may be more appropriate than a prescriptive deem-to-satisfy approach.

## THE NEED FOR MONITORING

Currently, the most predominant process associated with concrete deterioration is the ingress of water contaminated with chloride from de-icing salt used on roads during the winter months, or from the marine environment where, for example, bridges span tidal estuaries. In addition, the extent of reinforcement corrosion, freeze thaw damage, sulphate attack and alkali silica reaction all depend on the availability of moisture.

Deterioration of reinforced concrete due to chloride ingress is a significant drain on bridge maintenance resources, not only in terms of the remedial work required, but also in the costs associated with periodic inspections and testing. 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 repair options, and scheduling of inspection and maintenance programmes thereby minimising traffic delays resulting from road closures.

The ability to monitor the covercrete - as a function of time and depth - would assist in assessing the current and future performance of the cover-zone. The development of sensor systems to study covercrete performance and durability, forms one important component of an overall integrated monitoring system. When data from monitoring systems are used with improved service-life prediction models, additional savings in life cycle costs could result.

According to Schieβl and Raupach [Schieβl and Raupach, 1996], there are three broad levels of monitoring designated: high, medium and low, and the appropriate level must be considered at the design stage. As part of a high-level programme, the installation of sensors within the covercrete should be considered. The system reported here is based on a sensor arrangement that allows electrical measurements to be taken within the covercrete. Such measurements are technically simple to obtain and can be presented in a range of formalisms to allow ease of data interpretation.

## ELECTRICAL COVERCRETE SENSORS

Once passivity is lost, the electrical conductivity of the concrete surrounding the rebar is an important parameter in the corrosion process. A concrete with a low conductivity (high resistivity) would be indicative of a low corrosion rate, regardless of chloride concentration. Although it is recognised that the electrical conductivity of concrete is important, there is a dearth of information linking this parameter with corrosion initiation and propagation. The overall focus of the work, of which the system reported here is a part, is the attempt to correlate the electrical properties of concrete within the cover-zone and their variation with time with the conditions which 'trigger' and sustain corrosion. The electrical conductivity of concrete could thus be developed as a key parameter in assessing reinforced concrete durability.

The primary function of a covercrete sensor system is to provide real-time data on the condition of the covercrete and the spatial distribution of cover-zone properties. In order to study water, ionic and moisture movement within the surface zone, an embedded covercrete electrode-array, the details of which are given in previous laboratory based studies [McCarter, W. J., Emerson, M. and Ezirim, H., 1995; Chrisp T. M., McCarter W. J., Starrs G., Basheer, P. A. M. and Blewett, J., 2002], has been developed by the authors that allows discretized electrical resistance measurements to be taken through the depth of the concrete cover. In summary, the sensor comprises up to 10 electrode pairs mounted on a small Plexiglas former (Figure 1). Each electrode comprises a stainless steel pin (1.6 mm in diameter) which was sleeved to expose a 5mm tip; in each electrode pair the pins have a (horizontal) centre to centre spacing of 5 mm.

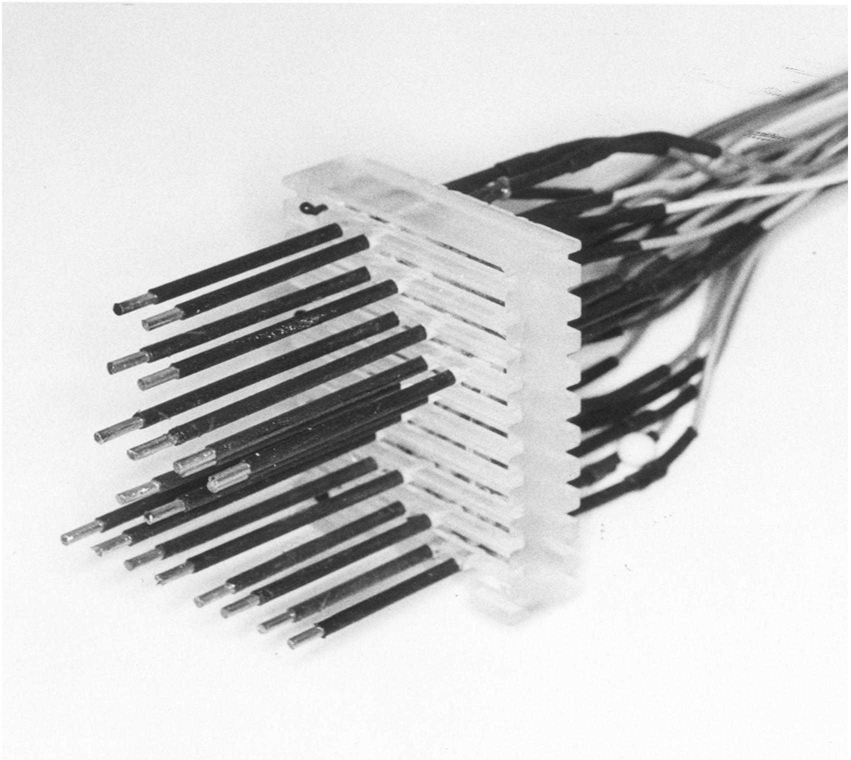


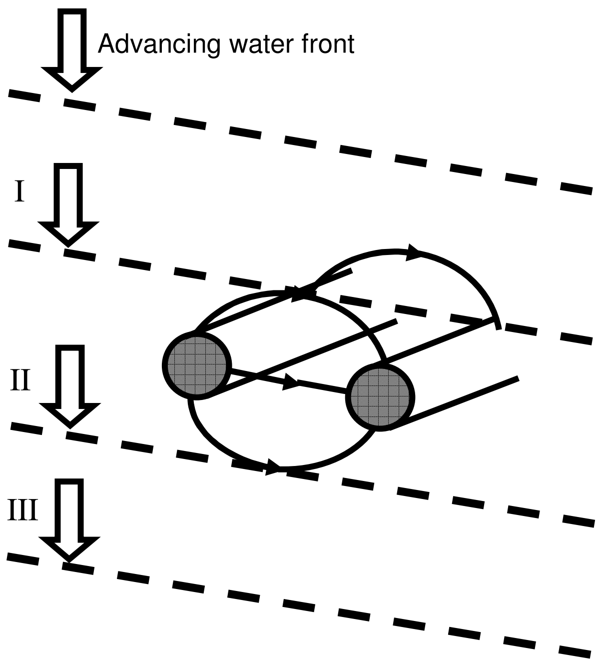
Figure 1 – Sensor Arrangement

The pairs of electrodes are then arranged vertically at 5 mm intervals thus enabling electrical measurements to be taken at discrete points over a depth of 50 mm. In addition, and to allow improved distribution of the concrete around the probe, the electrode pairs are off-set from each other in both the horizontal and vertical planes; also, the exposed tip of the electrode is positioned remote from the plexiglas former (> maximum aggregate size + 5mm). Four thermistors, positioned at 10, 20, 30 and 40mm from the exposed surface, enable temperature profiles to be obtained within this region.

The typical response of the measured resistivity to a moisture front advancing into the cover region is illustrated in the schematics of Figs. 2(a) and 2(b). As would be anticipated resistivity at any depth is seen to conform to one or more of the following regions:

(I) An initial region where $\rho$ remains virtually constant. At this stage the water-front is distant from the region of influence of the electrical field between the electrode-pair and hence no decrease in $\rho$ would be detected. In some instances, a small transient increase in $\rho$ has been detected, more significant for the deeper electrode levels, implying that as the water-front moves into the partially saturated concrete a volume of air is pushed ahead of it which disperses into the capillary pores;

(a)




(b)

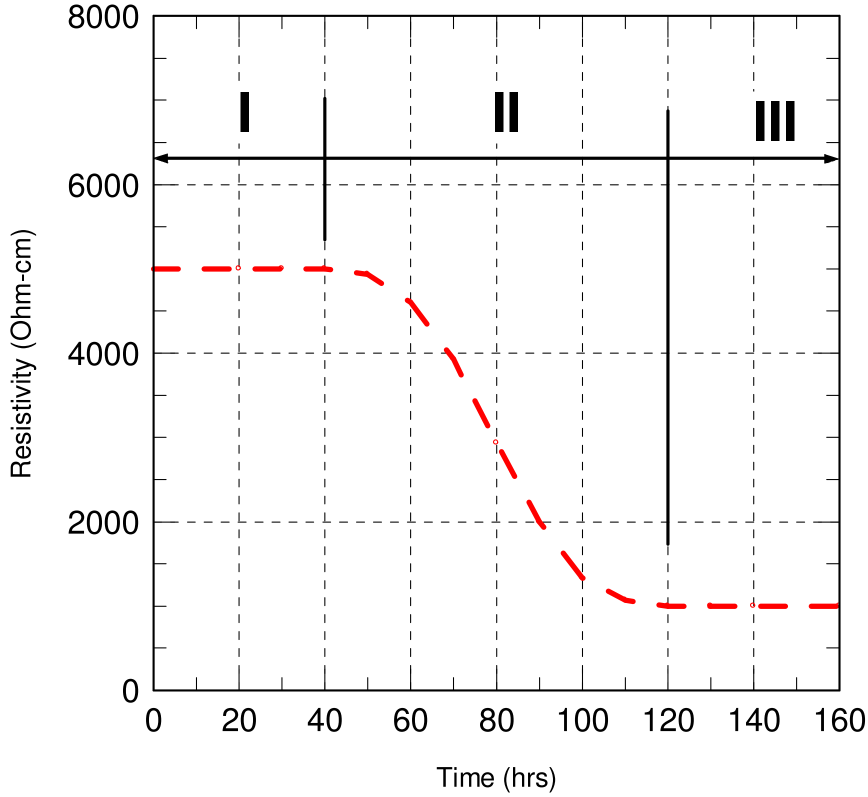



Figure 2 – Moisture absorption schematics
a) Electrode layout; b) Resistivity plot

(II) A decreasing portion of the curve where the advancing water-front moves into the vicinity of the electric field between the electrodes and eventually beyond its zone of influence. Over this period, the resistivity of the concrete decreases as the water-front eventually makes contact with the electrodes;

(III) A region where resitivity remains constant with time. When a steady state ρ value has been achieved at a particular depth, the water-front has advanced beyond the zone of influence of the electrical field between the electrodes at that particular level. The void network (i.e., connected capillary pores and microcracks) is considered to be fully saturated at that electrode level.

## MARINE EXPOSURE SPECIMENS (DORNOCH, SCOTLAND)

Previous research during development of the sensor revealed the necessity of regular monitoring during a structures life [McCarter, W. J., Butler, A., Chrisp, T. M., Emerson, M., Starrs, G. and Blewett, J.]. Such studies have shown that it is the wetting and drying cycles that can have the biggest effect on, for example, chloride ingress, and consequently regular readings need to be taken throughout the year to build up the correct picture. A Marine Exposure Site, set up on a marine tidal estuary in Dornoch, Scotland provides an ideal environment for such enhanced research. The site was set up in 1998 with samples exposed to continuous tidal cycling, splash and airborne spray (Figure 3). This allows monitoring of moisture movement throughout a complete tidal cycle using specimens that have been hard-wired to the site communications box to record the change of moisture and ionic condition in the cover-zone concrete as the tide rises and falls. Data have been, and are, obtained from concrete samples exposed to a marine environment. The specimens are positioned vertically in galvanised steel frames at three locations: above high water mark (denoted high-level), just below high water-mark (denoted mid-level) and just above low-water mark (denoted low-level). In accordance with reference [European Committee for Standardization (CEN), EN206-1, 2000] these are classified as, respectively, exposure classes XS1, XS3 and XS2; in addition, the exposed sample surfaces all face in a north-easterly direction.

These readings have been repeated over several years to build up a database and understanding of chloride ingress in such exposure conditions. From the results gathered from these specimens it is becoming possible to determine a relationship between corrosion activity on the bar surface and conductivity of the surrounding concrete and hence establish the conditions that are likely to trigger corrosion for chloride penetration caused by tidal action.

| Mix Designation | PC kg/$^3$ | PFA kg/m$^3$ | GGBS kg/m$^3$ | 20mm kg/m$^3$ | 10mm kg/m$^3$ | fines kg/m$^3$ | Plast. l/m$^3$ | w/b | Slump (mm) | $F_7$ MPa | $F_{28}$ MPa |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CEM I 42.5N | 460 | - | - | 700 | 350 | 700 | 1.84 | 0.4 | 105 | 57 | 70 |
| CEM III/A 42.5N | 270 | - | 180 | 700 | 375 | 745 | 3.60 | 0.44 | 140 | 31 | 53 |
| CEM II/B-V 42.5N | 370 | 160 | - | 695 | 345 | 635 | 2.65 | 0.39 | 110 | 33 | 58 |

**Table 1** Concrete mixes used in the testing programme.
(Plast. = plasticizer (Sika FR); w/b = water-binder ratio)

The cements used were Portland cement (PC), PC blended with granulated blast-furnace slag (GGBS) and PC blended with pulverised fuel ash (PFA) designated, respectively, CEM I 42.5N, CEM III/A 42.5N and CEM II/B-V 42.5N by EN 197-1 [European Committee for Standardization (CEN), EN 197-1, 2000]. Table 1 presents the mix details together with the mean 7- and 28-day compressive strength determined on 100mm cubes (denoted $F_7$ and $F_{28}$); a gravel aggregate and washed concreting fines were used throughout. Samples took the form of 300 x 300 x 200mm (depth) blocks. The covercrete electrode array was secured within the surface zone and at the centre of the 'working face' of each sample. The blocks were lightly reinforced with two, 16mm diameter rebars (200mm in length) which had a 50mm cover from both the working face and side faces. Cabling from the electrodes and thermistors was taken into a watertight glass reinforced plastic box cast into the face opposite to the working face. Specimens are sealed on five faces with a high-build epoxy coating, with the working face left unsealed. A total of 45 samples were deployed at the marine site, with six samples of each mix in Table 1 placed at the low- and mid- level locations, and three samples of each mix placed at the high-level location (Figure 4).

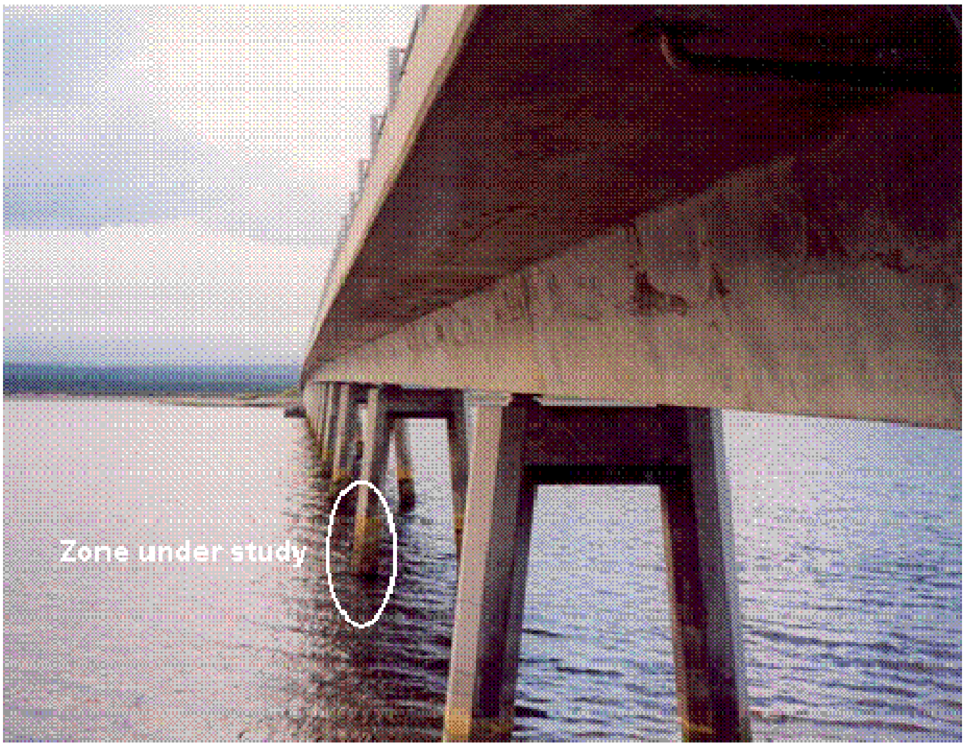



Figure 3 – Zone of Investigation

Figure 4 – Samples in XS3 Zone

## Calibration and Data Logging

The measurement system used for site data collection has developed through several stages. Currently, electrical measurements from the sensor are obtained using an auto-ranging resistance logger (custom designed for the Heriot-Watt University research group by Instrument Solutions) which measures the resistance of an electrode pair using an AC voltage of 1000mV at a single fixed frequency of 1000Hz. The logger was originally designed to log resistance data into non-volatile memory, for later recovery using a portable computer connected by an RS232 serial port cable. Previous studies indicated that the chosen operating voltage amplitude and frequency would ensure electrode polarisation effects were minimised [McCarter, W. J. and Brousseau, R., 1990]. Thermistor measurements were also logged using the same system.

The measured electrical resistance (R, in ohms) of the concrete can be converted to resistivity (ρ, in Ohm-m or Ohm-cm), or its reciprocal conductivity (σ, in Siemens/m), using a calibration constant for the covercrete array which was evaluated from a wide range of measurements on solutions of known conductivity carried out prior to installation.

# DATA LOGGING OF CONCRETE RESISTANCE BY REMOTE ACCESS

The general approach currently to structural monitoring, particularly in remote or difficult to access sites, involves site visits by engineers typically using handheld equipment for electrical measurements. This limits the frequency of data reporting to perhaps once a year, or even less, and provides only ‘snapshot’ views of covercrete condition, missing entirely the seasonal wetting and drying variations which are likely to occur. The cost of travel and subsistence for the personnel involved in site visits also makes more frequent monitoring too expensive for commercial practice.

## Remote Interrogation System at Dornoch Site

In order to improve data collection and reduce the need for site visits the authors have developed a remote interrogation system. This is currently on trial at the remote Dornoch Bridge marine test site. The new system is based on the embedded-sensor/data-logger described above and allows continuous electrical monitoring of covercrete in the previously described sample slabs, and remote access to stored data via a mobile phone network. At present the system lacks fully automated software control so that data download and inspection/interpretation are still initiated by the responsible engineer/researcher. The system, however, is self powering (solar), operates continuously, and can be accessed at any time from the research base at Heriot-Watt University for data acquisition and status checks, and to upload measurement configurations.  This removes the need for frequent site visits for these routine tasks.

The system is powered by a heavy duty battery supplied from a solar panel.  Charge from the solar panel to the battery is controlled, to prevent overload, by a Steca charge controller, which also acts as the voltage/current source for the logging and communications components of the system.

The centre of the system is the Instrument Solutions Resistance Data Logger which acquires and stores electrical resistance data.  The logger is interfaced to the chosen sample covercrete sensors via a six channel multiplexer unit.  The communications interface with the logger, at the site, is provided by a GSM modem using a 'dial-up' approach, necessary to maintain compatibility with the existing logger design.  A PC mounted software utility is used to establish a data connection to the modem, effectively creating a transparent link between the computer and the logger serial port. Data is then recovered in the same way as a direct RS232 connection, using straightforward ASCII commands via a standard 56k dial up modem connected to the PC.  The modem communicates via a small antenna mounted alongside the solar panel and the cables from both are routed through a secured protective conduit to the power and communications components of the system. The GSM Modem is fitted with a SIM card supported by a mobile airtime contract.

The logger operates using a 'wake / sleep' mode that reduces overall power consumption by drawing minimal current between logging events. In order for the modem to answer calls, it must be powered continuously but only draws about 10% of full power when not actively communicating. The Data Carrier Detect line on the modem serial port is then used to wake up the logger when an incoming data connection is detected.  Further power reductions are possible by fitting the modem power supply with a timer set to come on for a predetermined period convenient for data recovery.

The resistance logger, modem, charge controller and battery are housed in a robust weather resistant cabinet which is mounted on the side of the pier stem to which the solar panel is attached.  The multiplexer unit is housed in a similar adjacent cabinet into which the input signal cables from the covercrete sensors are connected.  The multiplexer control line connecting the units also carries power from the charge controller to the multiplexer.

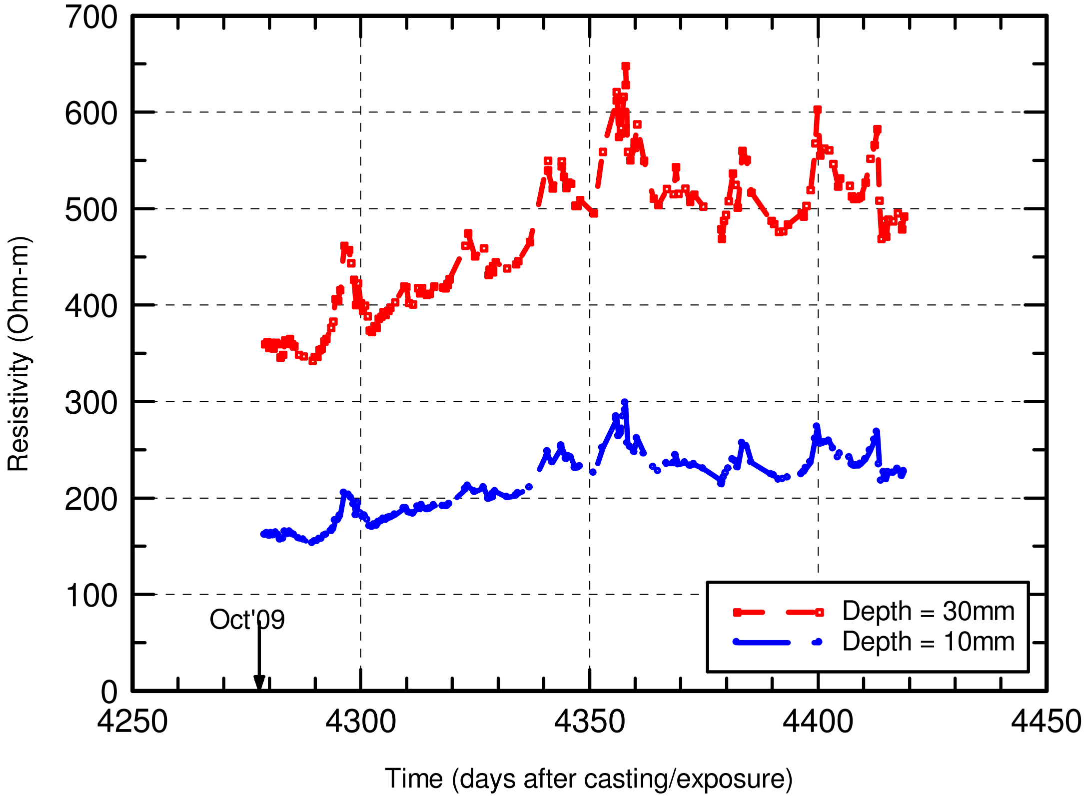
## RESULTS AND DISCUSSION

The concrete specimens detailed above have been undergoing longterm exposure testing and are now entering their eleventh year of exposure. Early electrical readings were taken by visiting the site. More recently the modem based logging system has facilitate the recovery of readings remotely. The measurements presented in this paper were recovered within the last year with the remote logging system.

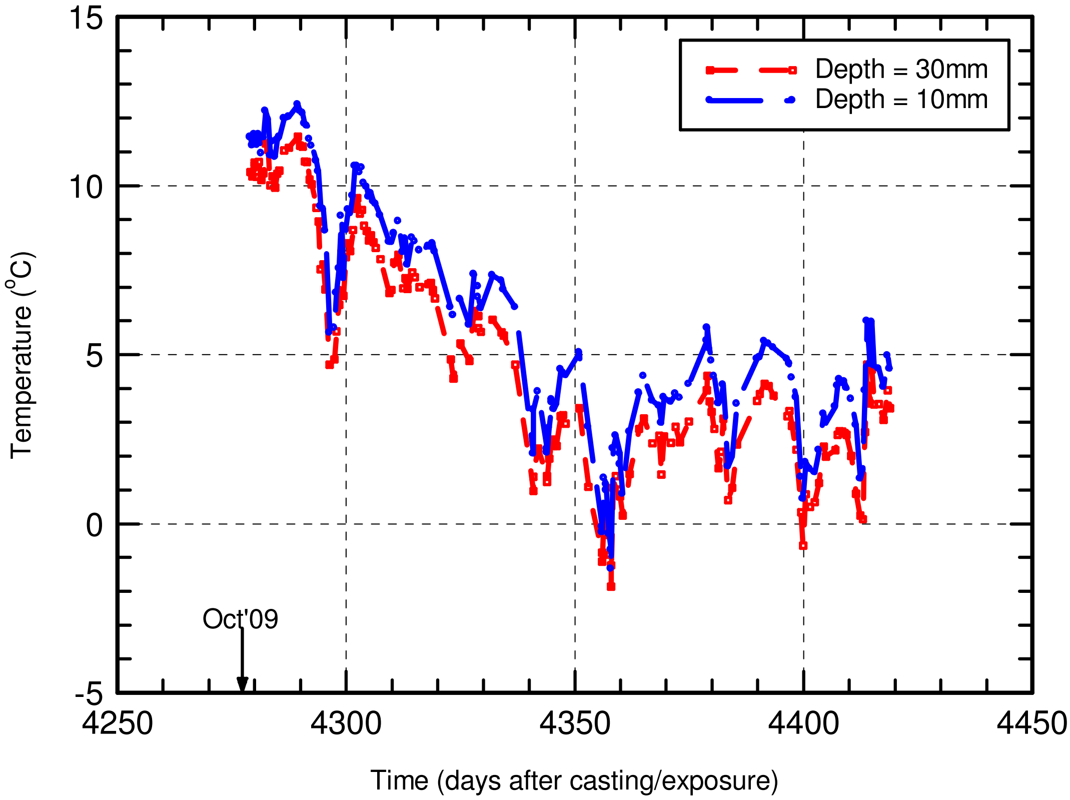
As data are recorded every two hours this gives, virtually, continuous real-time monitoring; however, due to the large amount of data collected only a selection of figures are presented to highlight the response of the covercrete to the ambient environment; specifically, the influence of temperature on the electrical conductivity is highlighted and correction procedures proposed.

Figure 5(a) presents the variation in resistivity at a depth of 10mm and 30mm from the surface of a concrete 'mini-slab' specimen over a six month period (October 2009 onwards); Figure 5(b) displays the change in both air temperature and covercrete temperature at depth of 10mm and 30mm over the corresponding period.

Concrete exposed to the natural environment is subjected to temperature variations and its electrical resistivity will fluctuate in sympathy with the concrete temperature. When undertaking electrical measurements on concrete it is important to distinguish between changes in resistivity due to changing levels of pore saturation, and/or ionic concentration within the pore-fluid, and those due to changes in ambient temperature.




(a) Recorded resistivity data




(b) Recorded temperature readings

Figure 5 - Raw data recovered from Marine exposure site - Mix CEMII (OPC+PFA)

At the measurement frequency (1kHz), electrical resistance through concrete is dominated by ionic conduction effects and will, as a consequence, be temperature dependent [14]. In the current work, an Arrhenius relationship is used to model the influence of temperature on resistivity, viz:

$$R = A.e^{-\left[\frac{E_a}{R_t.T}\right]} \qquad \text{.... (1)}$$

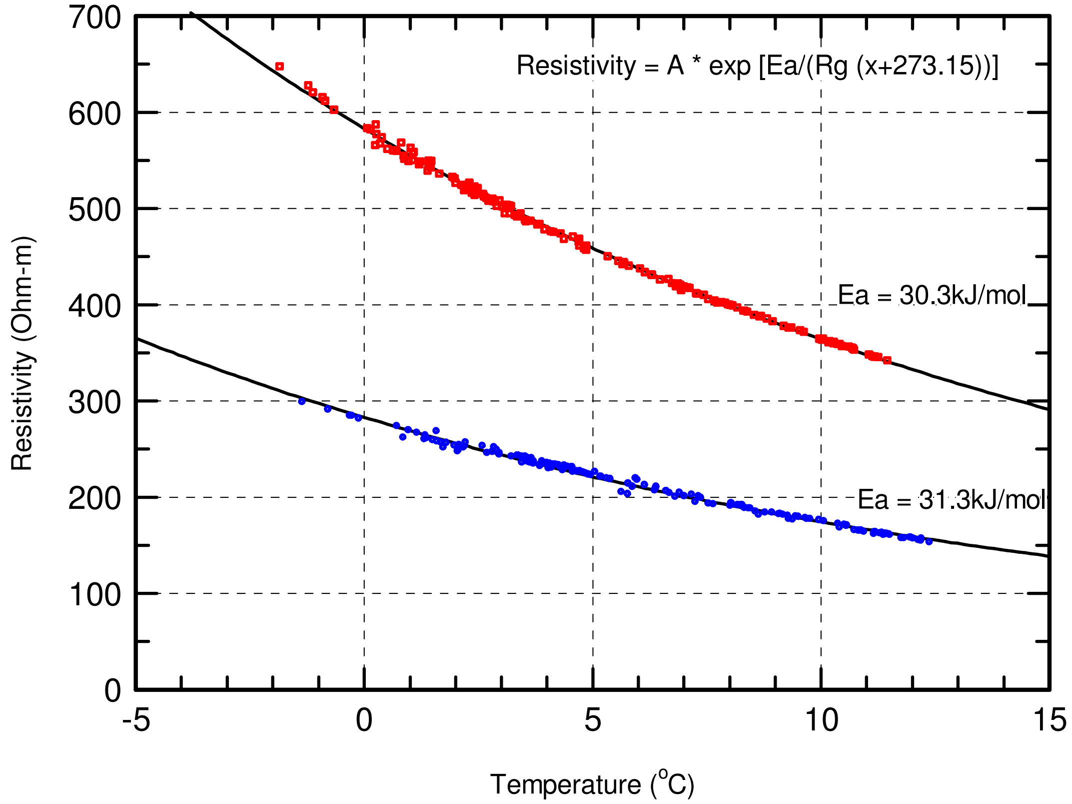
where ***R*** is resistivity (Ohm-m); *T* is temperature (°K); *A* is the nominal resistivity at infinite temperature (Ohm-m); *Ea* is activation energy for conduction (kJ/mole); and *Rg* is the gas constant, 8.3141kJ/mole/K.

Now, if ***R****x* and ***R****y* are the resistivities at temperatures *Tx* and *Ty*, respectively, then, from equation (1) above,

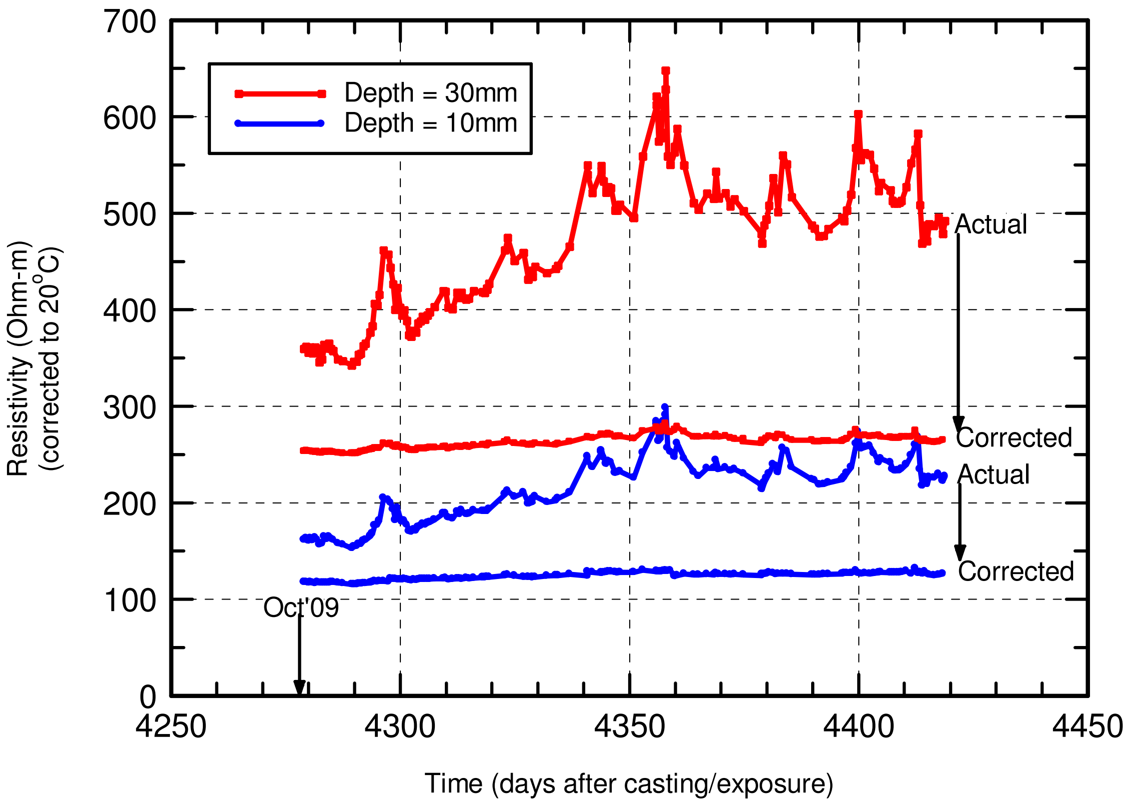
$$R_x = R_y.e^{-\frac{E_a}{R_g}\left[\frac{1}{T_x}-\frac{1}{T_y}\right]} \qquad \text{.... (2)}$$

Equation (2) implies that a value of resistivity, R*y*, recorded at a temperature *Ty* could be corrected for temperature by *standardising* [Chrisp, T. M., Starrs, G., McCarter, W. J., Rouchotas, E. and Blewett, J., 2001; Castellote, M., Andrade, C. and Alonso M. C., 2002] the as-measured resistivity to an equivalent resistivity, ***R****x*, at a reference temperature, *Tx*, through a knowledge of the activation energy, *Ea*, for the conduction process. The limited data available in the literature would indicate values of *Ea* for conduction processes in laboratory samples (cement pastes and mortars) typically lying in the range 15-30kJ/mole.

The in-situ measurements displayed in Figure 5(a) are now presented in Figure 6(a) in Arrhenius format (i.e. equation (2) above). From these measurements, the activation energy, ***Ea***, can be obtained for each electrode pair. The temperature measurement nearest to that electrode pair is used in this determination. In this way, the in-situ measurements can *fine-tune* the activation energy, which is more appropriate than using a laboratory determined value. The activation energy is constantly updated as more temperature and concrete resistivity measurements become available to provide feed-back into the Arrhenius equation.

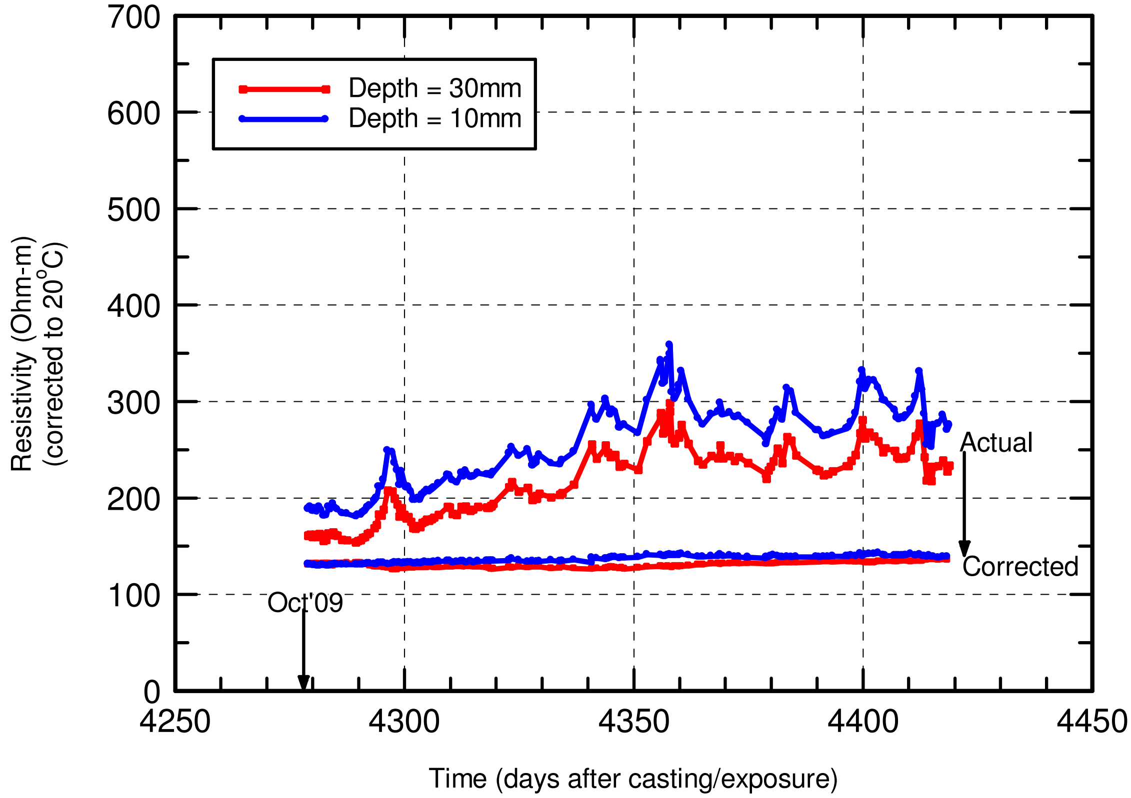



(a) Calculation of Activation Energy by curve fitting to gathered data

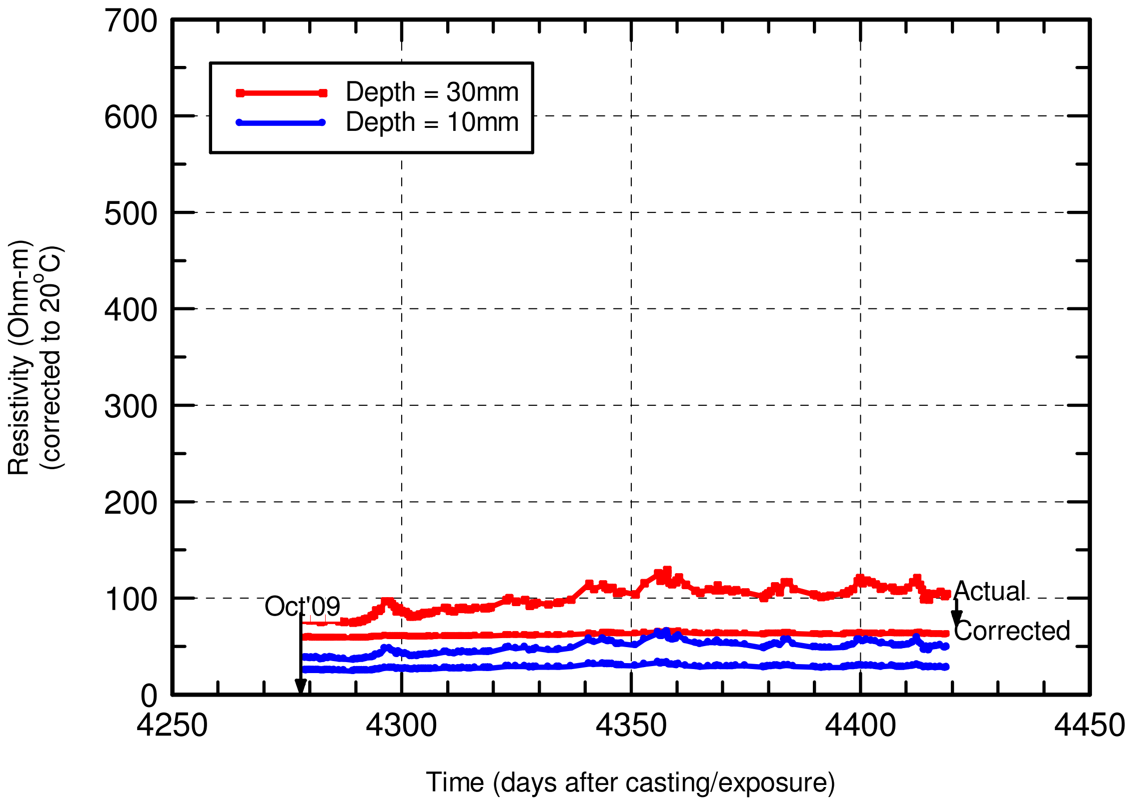



(b) Calculated resistivity corrected to 20$^{O}$C equivalent

Figure 6 - Processed data – Mix CEMII (OPC+PFA)




(a) Calculated resistivity corrected to 20$^{O}$C equivalent – Mix CEMII (OPC+GGBS)




(b) Calculated resistivity corrected to 20$^{O}$C equivalent – Mix CEMI (OPC)

Figure 7 - Processed resistivity data

It should be noted, however, the as-measured resistivity values are also of importance as, once depassified, corrosion rate is a function of the resistivity of the concrete between the anodic and cathodic areas on the rebar. There is now a considerable amount of published work to indicate a direct relationship between corrosion rate and concrete resistivity [Broomfield, J. P., 1997]. Hence, as the temperature of the concrete decreases, it becomes more resistive and, as a consequence, the corrosion rate will be reduced.

Having obtained the activation energy appropriate for each electrode pair on the array, the resistivity values can now be standardised to a reference temperature. For illustrative purposes, the data presented in Figure 5(a) were standardised to a reference of 20°C and are presented in Figure 6(b). It is immediately apparent that, once temperature effects have been *removed* from the resistivity values, the 10mm and 30mm electrode levels display only minor fluctuations over the period as they are effectively in a fully saturated condition.

Figure 7(a) and (b) show similar insitu-measured and corrected data for Mixes CEM II and CEM I respectively. It is noted how the background resistivity presented for the CEM I mix (OPC) is much lower than that of the other two mixes – CEM I 30to 60 Ohm-m; CEM II 120-130 Ohm-m; and CEM III 120 to 270 Ohm-m.

CONCLUDING COMMENTS

The electrical resistivity of concrete is now recognised as an important parameter which could be developed to assess concrete durability. However, resistivity is temperature dependent and in order to interpret and compare field data, measurements must be standardised to a reference temperature. In the current work, a temperature correction protocol was developed and based on an Arrhenius relationship to evaluate the activation energy for the conduction process. The important aspect of the work lies in the use of field data to evaluate and *fine-tune* the activation energy for each electrode level on the embedded electrode array.

**ACKNOWLEDGEMENTS**

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