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A Remote Interrogation System for Monitoring Concrete Performance Exposed to Environmental Action

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A remote interrogation system for monitoring concrete performance exposed to environmental action.

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ABSTRACT

The performance of the surface zone of concrete is acknowledged as a major factor governing the rate of deterioration of reinforced concrete structures as it provides the only barrier to the ingress of water containing dissolved ionic species such as chlorides which, ultimately, initiate corrosion of the reinforcement. In-situ monitoring of cover-zone concrete is critical in attempting to make realistic predictions as to the in-service performance of the structure. To this end, this paper presents developments in a remote interrogation system to allow continuous, real-time monitoring of the cover-zone concrete from an office setting. Use is made of a multi-electrode array [19] embedded within cover-zone concrete to acquire discretized electrical resistivity and temperature measurements, with both parameters monitored spatially and temporally. On-site, instrumentation, which allows *remote* interrogation of concrete samples placed at a marine exposure site, is detailed, together with data handling and processing procedures. Site-measurements highlight the influence of temperature on electrical resistivity and an Arrhenius-based temperature correction protocol is developed using on-site measurements to standardize resistivity data to a reference temperature; this is an advancement over the use of laboratory-based procedures. The testing methodology and interrogation system represents an additional technique which could be used for intelligent monitoring of reinforced concrete structures.

Keywords: Concrete, performance, remote monitoring, electrical resistivity, Arrhenius, temperature.

1.0 INTRODUCTION

The premature deterioration of concrete highway structures due to corrosion of the steel reinforcement is a world-wide problem. In the UK, as in most developed countries, the infrastructure has now reached an age where capital costs have decreased, but inspection and maintenance costs have grown, constituting 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 [1]. Demands for enhanced performance create a pressing need to be able to determine, with an acceptable degree of confidence, the anticipated service life of concrete structures. Deterioration of reinforced concrete due to corrosion 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.

Current testing methods tend to be intrusive, time-consuming and costly, both in terms of the direct costs involved and in the indirect costs such as traffic management, road closures and diversions required during inspection and testing. In the management of structures, monitoring the performance of the concrete could allow early detection of deterioration and hence assist in the implementation of appropriate repair strategies. The development of integrated monitoring systems for new reinforced concrete structures could reduce costs by allowing timely maintenance interventions and a more rational approach to the assessment of repair options and co-ordination and scheduling of inspection and maintenance programmes.

Integrated monitoring systems and procedures thus have an important role to play in the total management of structures as this involves both whole-life costings and service life calculations. When data from monitoring systems are used with improved service-life prediction models additional savings in life cycle costs could result thus offsetting the up-front installation costs of such monitoring systems.

2.0 BACKGROUND

Deterioration in concrete comprises an initiation period and a propagation period. The initiation period is characterised by changes that occur within the concrete cover zone 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 deterioration processes 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 concrete to the changing ambient environment in the vicinity of a specific structural element or part of a structure. Currently, the most predominant process associated with concrete deterioration is the ingress of water contaminated with chloride ions. Chloride ions come from deicing salt used on roads for winter maintenance purposes 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.

Since it is the concrete cover-zone which protects the reinforcing steel from the external environment (i.e. surface 50mm or so), it is understandable that the protective properties of this zone are crucial in attempting to make predictions as to the in-service performance of the structure with regard to likely deterioration rates for a particular exposure condition and compliance with specified design life. The ability to continuously monitor the cover-zone would thus allow a more informed assessment of the current and future performance of reinforced concrete structures. The development of sensors and associated monitoring systems to assess cover-zone performance would thus form an important component in the inspection, assessment, maintenance and overall management of structures.

This paper presents developments in a monitoring system which could be exploited for intelligent monitoring of reinforced concrete highway structures. In this context, intelligent monitoring is defined as *'automated monitoring which explicitly provides information on current condition and deterioration rates to assist in predicting the remaining life of a component or structure'* [2]. The focus of the work presented highlights the applicability of an embedded sensor array and associated remote monitoring system allowing interrogation from the office setting thereby providing virtually continuous, real-time data on the performance of cover-zone concrete exposed to natural environments.

3.0 TESTING METHODOLOGY

Regarding cover-zone properties, it is the permeation properties which are important and terms such as diffusivity (moisture and ionic), permeability (air and water) and sorptivity are used in this respect [3]. As a result, a number of surface-applied techniques have been developed and used to assess permeation properties [see, for example, 4-10] although their direct application in the field-environment has been limited as the moisture state of the concrete is unknown.

Since the flow of water under a pressure gradient, hence permeability, or the movement of ions under a concentration gradient, hence diffusivity, is analogous to the flow of electrical current under a voltage gradient it is understandable that the electrical resistivity of the concrete (or, its reciprocal, conductivity) could be of practical significance in assessing the durability of concrete structures [11-13]. Furthermore, once passivity is lost, research indicates that the single most important factor affecting the corrosion rate of the reinforcing steel is the resistivity of the surrounding concrete [14-18].

4.0 REMOTE INTERROGATION AND FIELD MONITORING PROGRAMME

4.1 Electrical Measurements

The Authors have utilized a multi-electrode array [19] which can be embedded within the cover-zone to allow monitoring of the spatial distribution of electrical resistance; such measurements can be correlated with water and ionic movement within the surface region [20, 21]. The array also has the facility to monitor temperature distribution through the cover region. In summary, the array comprises a series of electrode pairs mounted on a PVC, T-shaped former, with the former being secured onto two steel bars as shown in Fig. 1. These bars allow attachment of the array to reinforcement and their length can be tailored to suit the reinforcement detailing; the bars are electrically isolated from the steel reinforcement at the points of contact. Each electrode on the array comprises a stainless steel pin sleeved to expose a 5mm tip; in each electrode pair the pins had a (horizontal) centre to centre spacing of 5mm. The pairs of electrodes were positioned at 5, 10, 15, 20, 30, 40 and 50 from the base of the former (Fig. 1). Four thermistors are also mounted on the former and positioned at 10, 20, 30 and 40mm from the concrete surface to enable temperature measurement. Prior to installation, the electrodes on the array are calibrated in solutions of known resistivity thereby enabling the measured resistance, R (in ohms), to be converted to resistivity, ρ (in ohm-cm), or conductivity, σ (in Siemens/cm, S/cm), hence,

$$\rho = \frac{1}{\sigma} = \boldsymbol{k}R \quad \text{ohm-cm} \qquad [1]$$

where $\boldsymbol{k}$ is the calibration factor for the array which was 1.25cm ±5% and represented an averaged value over the electrode pairs.

Electrical resistance measurements were obtained using an auto-ranging logger which measured the resistance of the concrete between each electrode pair using an a.c. voltage of amplitude 1.0V at a fixed frequency of 1kHz. Previous studies indicated that the chosen operating voltage and frequency would ensure electrode polarisation effects were minimised [22]. Thermistor measurements were also acquired using the same system. The logger served a dual purpose as it also acted as the system controller, further details of which are presented below.

4.2 Materials and Specimens

In the current trial work, concrete specimens were exposed to a marine environment to include the spray, tidal and submerged zones. Concrete mixes were chosen to satisfy the requirements for all exposure conditions specified in EN 206-1:2000 [23] and are presented in Table 1. Dredged river gravel and matching fine aggregate were used; the binders comprised CEM I 42.5N cement (Portland cement to EN197-1:2000); CEM I cement blended with ground granulated blast-furnace slag (GGBS to EN15167-1:2006); and CEM I cement blended with fly ash (EN 450-1:2005). Specimens were 300×300×200mm (thick) slabs, with the working face cast against plywood formwork. The array, similar to that described above, was placed at the plan centre of each slab. On demoulding, the samples were wrapped with damp hessian and polythene for a period of 7-days. All surfaces, apart from the surface cast against the formwork which was the exposed working surface, were then sealed with several coats of an epoxy-based paint to ensure 1-dimensional moisture and ionic movement. Cabling from the array was colour coded and taken into a watertight glass reinforced plastic (grp) enclosure placed in the face opposite to the working face; a 37 pin, multi-pole female D-connector was used to terminate all wires. The seal on the lid of the grp box had been pressure tested to 10 bar to ensure watertightness under hydrostatic head. A schematic diagram is presented in Fig. 2(a); Fig 2(b) displays a slab with the lid removed to show the grp enclosure and 37-pin, D-connector.

Eighteen (18) specimens of each mix were transported and placed at a marine exposure site on the Dornoch Firth (Scotland) (Fig. 3(a)) and secured in galvanised steel frames (Fig. 3(b)); six specimens/mix were positioned at three exposure environments [23],

(i) above high-water-level in the airborne spray zone; classed as XS1 exposure;

(ii) just below high-water-level in the tidal/splash zone; classed as XS3 exposure; and,

(iii) below mid-tide level; classified as the submerged zone; XS2 exposure.

4.3 Remote monitoring of cover-zone response

During the early stages of the study, site visits were required with measurements on the specimens recorded manually (Fig. 3(b)), however, due to the remoteness of the site, data collection was erratic. Clearly, in order to gain a more informed understanding as to how the cover-zone concrete is performing and its response to changing environmental conditions, the periodicity of data collection needed to be increased. As a consequence, the authors developed a system to allow remote interrogation of the specimens thereby providing virtually a continuous feedback of site data thereby eliminating the need for site visits. This system has been under trial since November 2009

In the current trial, a total of six samples were hard-wired back to the interrogation system (describe below) via individual multi-core cables: three samples, one of each mix, at the XS2 environment and a corresponding number at XS3 environment. In summary, 37-pin, male D-connectors were secured at the ends of the connecting cable – one end connected to the interrogation system and the other end connected to the female D-connector on the sample. The entire male-female connection (Fig. 2(b)) at the sample end was sealed in the grp box by flooding the box with an epoxy-based potting compound.

The interrogation facility at the exposure site comprises two watertight enclosures (Fig. 4(a)) secured to a concrete pier-stem, the latter forming part of another related research programme

[24]. One enclosure contains a multiplexing unit (Fig. 4(b)), the other contains the controller and resistance measurement circuitry (Fig. 4(c)). The multiplexing unit and controller are permanently connected. The cabling from the embedded arrays was connected to the multiplexing unit in Fig. 4(b), with a total of six samples connected to the unit in this trial. The communications interface with the controller is provided by a modem using a dial-up approach and a PC mounted software utility to establish a data connection to the modem, effectively creating a transparent link between the office-based PC and the serial port on the site-based system controller. Data are recovered in the same way as a direct RS232 connection using standard ASCII commands via the PC's modem. The controller is accessed via the mobile telephone network (Fig. 4(d)) and the entire system is powered by a battery which is trickle-charged via a solar panel (Fig. 4(d)). The time interval between measurement cycles is configured remotely from the office and, in this current trial, is set on a 12 hour cycle.

During a measurement cycle, cover-zone resistance and thermistor data are recorded for all embedded arrays, with each array returning seven resistance and four thermistor measurements which are subsequently stored by the controller. The systems then *sleeps* until the next measurement sequence is triggered by the controller. By operating on a *wake/sleep* mode, the overall power consumption is reduced 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 used to *wake-up* the controller when an incoming data connection is detected i.e. the system is interrogated from the office. The data stored by the controller can be accessed and downloaded at any time. If the storage capacity of the controller is exceeded a warning is returned to the office. All the measurements are returned from site as an Excel® spreadsheet which allows ease of data manipulation and is discussed below.

5.0 RESULTS AND DISCUSSION

This section presents data taken over the 150-day period after installation to highlight data handling and processing protocols. Due to the considerable amount of data collected, only typical measurements are presented for illustrative purposes.

5.1 Resistivity Measurements

Figs. 5(a)-(c) present the variation in cover-zone resistivity (in kohm-cm) for the three concrete mixes at XS2 environment (i.e. below mid tide level) over the initial 150-day period after installation of the remote interrogation system. Over the period presented (November–March), it is clear that,

(i) the resistivity of the samples with replacement materials (Figs 5(b) and (c)) is significantly greater than that of the samples with plain Portland cement binder (Fig. 5(a)). It is well known that these materials produce in a refinement in the microstructure/pore-structure which would result in a higher resistivity as shown by the data; however, detailed discussion of these resistivity measurements is outwith the scope of this paper.

(ii) the resistivity for the samples fluctuates markedly over the test period and it is evident that these fluctuations occur at similar times in all concrete mixes.

Regarding (ii) above, since electrical conduction through concrete will be dominated by ionic conduction effects via the continuous pore network between the electrodes it will, as a consequence, be temperature dependent [25, 26]. Whereas in the laboratory ambient temperature can be controlled, this is not the case for concrete exposed to the natural environment where the temperature can vary markedly. The discussion below outlines a protocol to standardise in-situ resistivity measurements to a reference temperature.

5.2 Cover-Zone Temperature

Thermistor measurements were converted to temperature using the Steinhart-Hart equation,

$$T = [A + B\,ln R + C(ln R)^3]^{-1} - 273.15 \tag{2}$$

where R is the measured resistance of the thermistor (ohms); T is the temperature (ºC); A, B and C are coefficients which depend on the type of thermistor, and *ln* is the natural logarithm. For the thermistors used in the current work, A, B and C were determined as, respectively, $1.28\times10^{-3}K^{-1}$, $2.36\times10^{-4}K^{-1}$ and $9.31\times10^{-8}K^{-1}$.

Fig. 6 displays the variation in mean cover-zone temperature (determined from the four thermistor values) for the concrete mixes presented in Fig. 5. It is apparent that the resistivity fluctuates in sympathy with the changing temperature and it is important to distinguish between changes in resistivity due to temperature effects, and changes in resistivity due ionic ingress, changing levels of moisture content or hydration effects.

An Arrhenius relationship is used to model the influence of temperature on resistivity viz,

$$\rho = \rho_o e^{\left[\frac{E_a}{R_g T_k}\right]} \tag{3}$$

where ρ is the resistivity (kohm-cm); T_k is the absolute temperature (K); ρ_o is the pre-exponential constant (kohm-cm); R_g is the gas constant (8.3141×10^{-3}kJ/mole/K) and E_a is the activation energy for conduction processes in concrete (kJ/mole). Now, if ρ_x and ρ_y are the resistivities at temperatures $T_{k,x}$ and $T_{k,y}$, respectively, then, from equation (3) above,

$$\rho_x = \rho_y e^{\frac{E_a}{R_g}\left[\frac{1}{T_{k,x}} - \frac{1}{T_{k,y}}\right]} \tag{4}$$

From equation (4), a value of resistivity, ρ_y, recorded at a temperature $T_{k,y}$ could then be used to obtain an equivalent resistivity, ρ_x, of the material a temperature, $T_{k,x}$, through a knowledge of the E_a/R_g ratio for the conduction process. This formalism enables measurements to be standardised to a reference temperature thereby removing the influence of temperature on electrical resistivity. In the current work, the reference temperature ($T_{k,x}$) is taken as 25ºC (298.15K).

4.3 Evaluation of E_a/R_g from In-situ measurements

The ratio E_a/R_g for the concrete between each pair of electrodes on the array can be obtained from the in-situ measurements and allows evaluation of this parameter for a particular concrete mix and electrode pair. Equation (3) can be written,

$$ln\rho = ln\rho_0 + \frac{E_a}{R_g T_k} \tag{5}$$

hence plot of $ln\rho$ versus $1/T_k$ will be a straight line of slope E_a/R_g . This value is then used in equation (4) to standardise the resistivity values to 25ºC. Using in-situ, site measurements are more relevant that determination of this value form controlled laboratory tests.

As way of illustration, Fig. 7 presents the resistivity values in Fig 5(a) for the CEM I concrete mix plotted against the mean cover-zone temperature in the format of equation (5) for data obtained over the initial 150-days. The E_a/R_g ratio (slope) obtained from these curves, and calculated activation energy (E_a) at each electrode pair, are presented in Table 2; for comparison, the respective values obtained for the other mixes are presented.

Having obtained values for the E_a/R_g ratio, the measured resistivity can now be standardised to the reference temperature using equation (4) above at each electrode pair on the array. Figs 8(a)-(c) display the measurements standardised to the reference temperature of 25ºC for these mixes. As the resistivity remains relatively constant over the test period, the fluctuations in resistivity measurements displayed in Fig. 5 are entirely due to changes in temperature. It also indicates that the Arrhenius approach is adequate in explaining the influence of temperature on electrical resistivity measurements and could be used as a procedure for standardizing field data.

5.0 CONCLUDING COMMENTS

The electrical resistivity of concrete is now recognised as an important parameter which could be developed to assess concrete performance hence durability. The work presented has developed a methodology for evaluating this parameter utilizing an embedded electrode array together with a remote interrogation system to allow access to data from an office setting. Further, the measurement of the electrical resistivity at discrete points allows an integrated assessment of both spatial and temporal change in cover-zone performance.

Data handling and processing procedures are detailed; specifically, the influence of temperature on field resistivity measurements is highlighted and a standardizing procedure presented which utilized an Arrhenius relationship between resistivity and temperature. An important aspect of the procedure entails the use if field data to evaluate the activation energy for a particular concrete and electrode pair. This ensures that temperature effects can be effectively *removed* from field measurements.

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	Mix Designation		
	CEM I 42.5N	CEM III/A	CEM II/B-V
OPC GGBS Fly Ash (kg/m^3)	460 -	270 180 -	370 - 160
20mm 10mm Fine (<4mm) (kg/m^3)	700 350 700	700 375 745	695 345 635
Water-Reducer (l/m^3)	1.84	3.60	2.65
w/b	0.4	0.44	0.39
F_{28} (MPa)	70	53	58

Table 1 Concrete mixes used in site trials (w/b = water-binder ratio).

Depth (mm)	CEM I 42.5N		CEM III/A		CEM II/B-V	
	E_a/R_g (K)	E_a (kJ/mole)	E_a/R_g (K)	E_a (kJ/mole)	E_a/R_g (K)	E_a (kJ/mole)
5	3554	29.55	+	+	3753	31.20
10	4027	33.48	4134	34.37	3651	30.35
15	3644	30.30	4040	33.59	3790	31.51
20	4167	34.64	4053	33.70	3725	30.97
30	4113	34.20	4012	33.36	3551	29.52
40	4160	34.59	3915	32.55	3817	31.73
50	4106	34.14	3920	32.59	3011	25.03

Table 2 E_a/R_g ratio determined from the equation (5) and Fig. 7; the activation energy E_a for electrical conduction processes is also presented. (**+** data lost for 5mm depth).

CAPTIONS FOR FIGURES

Fig. 1 The multi-electrode array.

Fig. 2 (a) Schematic diagram of embedded array and cable termination; and, (b) showing grp enclosure and lead termination at a 37-pin D-connector.

Fig. 3 (a) Location of marine exposure site, and (b) slabs secured in galvanised steel frames with the lid on the grp enclosures removed for (manual) data collection purposes.

Fig. 4 (a) Watertight enclosures for monitoring and telephony equipment; (b) termination of cabling from sensors at multiplexing unit; (c) combined system controller/measuring unit, battery and trickle-charger from solar panel; and (d) solar panel and aerial for wireless connection.

Fig. 5 Temporal and spatial variation in resistivity for (a) CEM I concrete mix (same legend for all Figures); (b) CEM III/A concrete mix (Note: data lost for 5mm depth), and (c) CEM II/B-V.

Fig. 6 Variation in (mean) cover-zone temperature for concrete mixes.

Fig. 7 Data in Fig. 5(a) plotted in Arrhenius format.

Fig. 8 Resistivity data in Fig. 5 standardised to a reference temperature of 25ºC using E_a/R_g values in Table 2 for (a) CEM I concrete mix; (b) CEM III/A concrete mix, and (c) CEM II/B-V (50mm depth has been omitted from (c) as it is considerably greater that 30kohm-cm).