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Conductivity Sensors to Monitor Cover-Zone Performance

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ABSTRACT. This paper presents developments in the use of an embedded, multi-electrode conductivity sensor to study the response of the concrete cover-zone to environmental action. The sensor enables an evaluation of the temporal and spatial variation of electrical conductivity thereby allowing an integrated assessment of the cover-zone. Conductivity sensors were embedded within concrete samples to study the cover-zone response to cyclic wetting and drying under laboratory conditions. This work was extended to include the use of remote interrogation methods to study samples placed at a marine exposure site and preliminary results are presented.

KEY WORDS: Concrete, Cover-zone, Conductivity, Durability, Monitoring.

1. Introduction and Background

It is understandable that a knowledge of the protective properties of the cover-zone is 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. Regarding cover-zone properties, it is transport processes which are important and terms such as diffusivity (both moisture and ionic), permeability and sorptivity are used in this respect. There clearly exists a need to study and determine quantitatively those near-surface characteristics of concrete which promote the ingress of gases or liquids containing dissolved contaminants and defining concrete performance in terms of a *durability parameter*.

The specification of service life of reinforced concrete structures by means a single parameter is a subject of increasing interest. Since the flow of water under a pressure gradient or the movement of ions under a concentration gradient is analogous to the flow of current under a potential gradient it is understandable that the electrical conductivity (or its reciprocal, resistivity) of the concrete is being increasingly considered as a *durability index*

for use in this respect. Conductivity can be directly related to pore tortuosity, pore connectivity and the degree of pore saturation, so its measurement could be of practical significance in assessing the durability of concrete structures. Furthermore, as the conductivity of the concrete surrounding the rebar controls the magnitude of the corrosion current this parameter plays an important role in corrosion dynamics.

Electrical conductivity is a relatively easy parameter to measure and the measurement technology also lends itself to remote monitoring and interrogation from an office setting. The installation of a network of conductivity sensors, embedded at critical locations within a concrete structure, could provide continuous, real-time data on the response of the micro-environment within the cover-zone to changing exposure conditions thereby allowing assessment of both the temporal and spatial dependence of degradation processes.

2. Experimental

This paper highlights the use a multi-electrode array embedded within the cover-zone of concrete specimens to facilitate real-time monitoring of both spatial distribution and temporal changes of electrical conductivity within the cover-zone. The work presented forms part of a more extensive research programme into monitoring and improving the performance of cover-zone concrete exposed to environmental action. Data are presented to highlight some of the information that can be obtained from discretized conductivity measurements within the cover-zone under a cyclic wetting/drying regime (laboratory conditions); also presented are preliminary results from a monitoring system currently being trialled allowing remote interrogation of specimens placed in a marine environment.

2.1 The Multi-Electrode Array

The array comprised 8 electrode pairs mounted on a small former; each electrode consisted of a stainless steel pin which was 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 50mm from the exposed surface (Fig. 1).



Figure 1. *The multi-electrode array*

Four thermistors were also mounted on the former and positioned at 10, 20, 30 and 40mm from the concrete surface to allow measurement of temperature gradients within the cover-zone; temperature measurements are also used to standardize conductivity measurements to a reference temperature. Prior to installation, the electrode arrays were calibrated thereby enabling the measured resistance, R (in ohms), to be converted to conductivity, σ (in Siemens/m, S/m), or its reciprocal resistivity, ρ (in ohm-m).

2.2 Materials, Samples and Curing

In the work presented, mixes were chosen to satisfy the requirements for virtually all exposure conditions specified in EN 206-1:2000. Crushed rock aggregate and matching fine aggregate were used; the binders comprised CEM I cement (EN197-1:2000); CEM I cement blended with ground granulated blast-furnace slag (EN15167-1:2006); and CEM I cement blended with fly ash (EN 450-1:2005). Specimens were 300×300×150mm (thick) blocks, with the working face cast against plywood formwork. The plywood formwork had been given a coat of proprietary release agent prior to casting. The multi-electrode array described in Section 3.1, 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 that was to be used as the exposed working surface, were then sealed with several coats of an epoxy-based paint to ensure 1-dimensional drying. Thereafter, samples were left in a laboratory (20°C ±1°C; 50-55%RH) until required for testing.

(i) *Laboratory Exposure*: after 7 weeks air-curing under laboratory conditions, water was supplied from a reservoir placed over the full suction surface (300×300mm²) of the sample (i.e. the bottom surface of the slab cast against formwork) and maintained for a period of 48-hours. The samples were then subjected to a cyclic regime of approximately 8 weeks drying followed by a further 48-hour water absorption, this continued over a period of approximately 15-months.

(ii) *Marine Exposure*: a total of 54 samples (18 of each mix) were placed at a marine exposure site on the Dornoch Firth (Scotland) and positioned at three environmental exposures: above high-water-level (airborne spray zone: XS1); just below high-water-level (tidal/splash zone: XS3), and below mid-tide level (submerged zone: XS2). This is discussed in detail below.

2.3 Measurements

In the laboratory studies, spot measurements were taken during the 48-hour absorption cycle and during the subsequent extended drying cycle. Electrical resistance measurements were obtained at a frequency of 1kHz for each electrode pair on the array and the four thermistors. Data were converted to concrete conductivity and temperature (the latter using the Steinhart-Hart equation with appropriate thermistor coefficients). The data logging system for site studies is described in Section 4.2 below.

Table 1. Summary of concrete mixes.

MIX	CEM I 42.5N	CEM III/A	CEM II/B-V
OPC	460	270	370
GGBFS	-	180	-
Fly Ash (kg/m ³)		-	160
20mm	700	700	695
10mm	350	375	345
finer (kg/m ³)	700	745	635
w/b	0.4	0.44	0.39
F ₂₈ (MPa)	70	53	58

3. Results and Discussion

3.1 Cyclic Wetting and Drying

The response of the electrode array to the cyclic wetting/drying regime is presented in Figure 2(a) and (b) for the plain concrete mix and the fly-ash mix, respectively. This Figure displays the change in conductivity (in S/m) for each electrode pair at the depths indicated; for clarity, the only the responses from 5, 10, 15, 30, 50mm are presented. Periods of wetting and drying are clearly evident: as water is absorbed into the partially saturated cover-zone, the conductivity increases, although the prominence of this increase diminishes with increasing depth. Where conductivity increases signifies that the wetting-front has penetrated into the zone of influence of the electrical field between that particular pair of electrodes. As electrical conduction through concrete will be dominated by ionic processes within the continuous, interstitial aqueous phase, it will be influenced by:

- (i) hydration and pozzolanic reaction (and chloride binding effects when chlorides are present). This has the effect of increasing pore constriction and tortuosity thereby decreasing conductivity over the longer term;
- (ii) surface drying effects which will decrease conductivity; and,
- (iii) water ingress, which will result in an increase in the measured conductivity (enhanced by chlorides, if present within the invading solution).

From Figure 2, it is evident that conductivity values display a general decrease in over the test period. This feature is more clearly seen at the electrodes positioned distant from the exposed surface and would be attributable to ongoing hydration and pozzolanic activity with water being made available from periods of absorption; the response for all concretes indicate that this activity continues throughout the test period with the fly-ash concrete undergoing the greatest reduction.

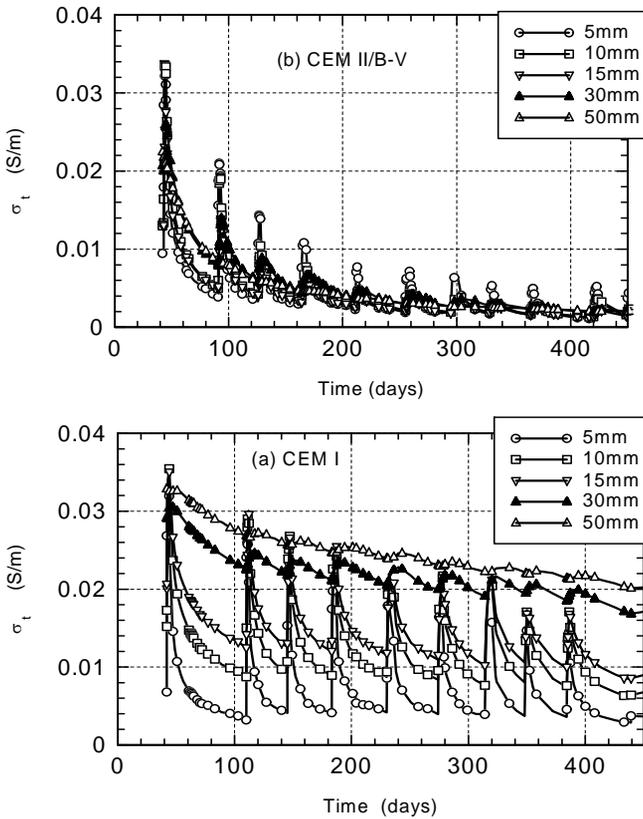


Figure 2. Cover-zone response to cyclic wetting and drying for (a) CEM I concrete mix, and (b) CEM II/B-V concrete mix.

Figure 2 clearly highlights the cover-zone response to the cyclic wetting and drying regime whereby the conductivity increases and decreases under, respectively, wetting and drying. This effect diminishes with depth through the cover. Regarding the latter, this is discernible for those electrodes positioned within the surface 30mm or so and would suggest that the antecedent period of drying has only influenced the surface 30mm of the cover-zone. Figure 3 presents conductivity versus depth profiles for the CEM I concrete specimen taken just prior to an absorption cycle and immediately after 48 hours ponding with water. The conductivity profiles after the period of drying increase with distance from the exposed surface and reflect the increasing degree of pore saturation with depth. After absorption, conductivity values, in some instances, can change by over and an order of magnitude with the most noticeable changes occurring over the surface 30mm. Considering the profiles before and after absorption, there is a point within the cover-zone where the profiles remain virtually unchanged; this point is taken as an estimate of the depth of the cover-zone most influenced by drying action prior to absorption i.e. the *convective zone*.

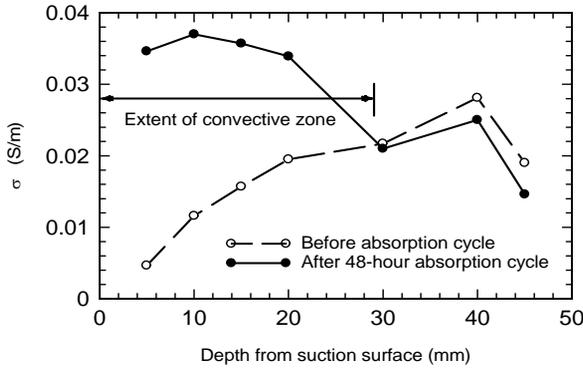


Figure 3. Convective zone estimated from conductivity measurements

3.2 Remote monitoring of cover-zone response

Samples with embedded sensor arrays were deployed at a marine exposure site on the Dornoch Firth (Scotland). Since November 2009, we have been trialling a system to allow remote interrogation of the sensor array (Figure 4). The system comprises two watertight enclosures (Figure. 4(a)) which contain a multiplexing facility (Figure. 4(b)) to switch between each sensor unit and the controller/measurement circuitry (Figure 4(c)); the cabling from the embedded sensors was hard-wired back to the multiplexing unit in Figure 4(b), with a total of six samples connected to the current system under trial. The system is accessed via the mobile telephone network and powered by a battery which is charged via a solar panel (Figure 4(d)). The time interval between measurement cycles is set remotely and, in this is current trial, is 12 hours. During a measurement cycle, cover-zone resistance and thermistor data are recorded for all sensor units which are subsequently stored by the controller; the systems then *sleeps* until the next measurement sequence is triggered. The data stored by the controller can be accessed and downloaded at any time.

Initial data are presented in Figures 5 and 6 (for CEM III mix: XS2 environment – below mid tide level). Figure 5(a) presents the variation in conductivity with time over the initial monitoring period and Figure 5(b) the temperature within the cover zone at depths indicated. Electrical conduction through saturated concrete will be dominated by ionic conduction effects and will, as a consequence, be temperature dependent. In the laboratory, where the temperature is stable, this does not cause a problem; however, for concrete exposed to the natural environment the temperature can vary markedly. This is evident from Figures 5(a) and (b) where the conductivity fluctuates in sympathy with the changing temperature. In attempting to interpret these measurements, it is important to distinguish between changes in conductivity due to temperature effects and changes in conductivity due ionic ingress, changing levels of moisture content or hydration effects.

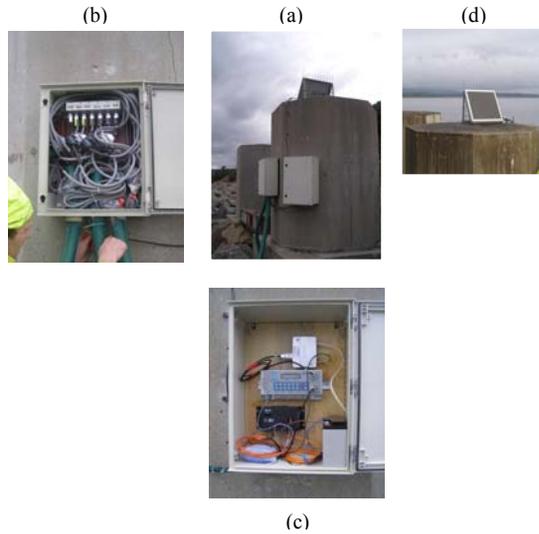


Figure 4. (a) Watertight housings for monitoring and telephony equipment; (b) termination of cabling from sensors at multiplexing unit; (c) combined system controller/measuring unit, battery and trickle-charger from solar panel; and (d) solar panel and aerial for wireless connection

The current work uses an Arrhenius relationship to *standardize* conductivity measurements to a reference temperature. The activation energy for the conduction process can be evaluated from the conductivity at a particular electrode-pair and the temperature from the neighbouring thermistor. Figure 6(a) presents the data in Figure 5 plotted in an Arrhenius format (temperature in Kelvin). Using in-situ measurements allows *fine-tuning* of the activation energy for the particular concrete mix/sensor, which is more appropriate than using a *blanket* value for all concretes. The activation energy is constantly updated as temperature and concrete conductivity measurements become available and provide *feedback* into the Arrhenius equation.

Figure 6(b) presents the data in Figure 5(a) standardized to a temperature of 20°C. It is evident that the erratic response due to temperature changes has been substantially *removed* with the standardized results at all depths displaying a gradual downward trend. This would suggest ongoing hydration, rather than ionic ingress which would cause an increase in conductivity. It should also be noted that the as-measured results presented in Figure 5(a) should not be ignored; if conductivity is to be used as a parameter in the assessment of corrosion rate, then it is the as-measured value that will be important. As the temperature of the concrete decreases, not only will the concrete be less conductive, but the anodic and cathodic reaction rates associated with a corrosion cell will also be reduced - i.e. the corrosion process will be slower at the lower temperature.

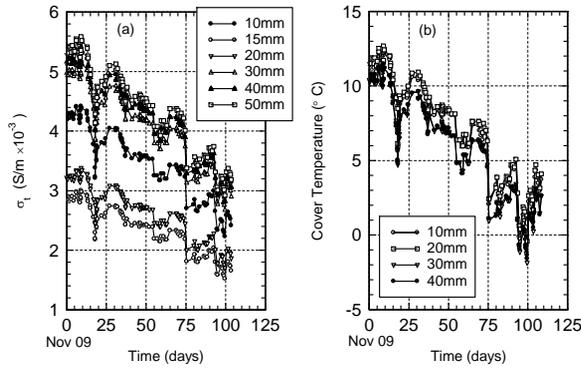


Figure 5. Variation in (a) as-measured conductivity, and (b) cover-zone temperature.

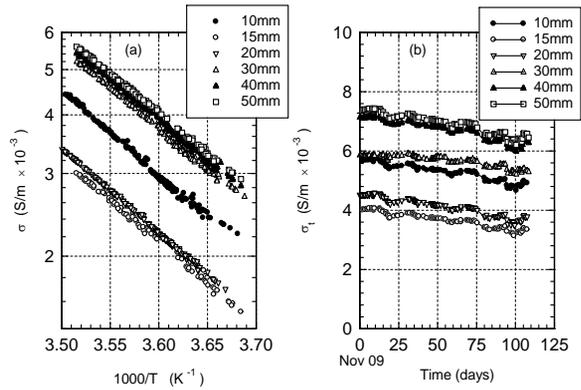


Figure 6. (a) Conductivity and temperature measurements plotted in Arrhenius format, and (b) conductivity measurements standardized to a reference temperature (20°C).

4. Concluding Comment

The sensor system outlined above can provide detailed information on spatial and temporal response of the cover-zone to the external environment. It has been shown that the sensor lends itself to remote integration thereby allowing virtually continuous, real-time monitoring of the performance of the cover-zone. Trials are continuing in this respect.

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