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## Performance Monitoring of Cover-Zone Concrete

Niall Holmes

*Technological University Dublin, [niall.holmes@tudublin.ie](mailto:niall.holmes@tudublin.ie)*

John McCarter

*Heriot-Watt University*

Malcolm Chrisp

*Heriot-Watt University*

Gerry Starrs

*Heriot-Watt University*

Sreejith Nanukuttan

*Queen's University - Belfast*

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## Authors

Niall Holmes, John McCarter, Malcolm Chrisp, Gerry Starrs, Sreejith Nanukuttan, Lulu Basheer, Niall Holmes, and Muhammed Basheer

# PERFORMANCE MONITORING OF COVER-ZONE CONCRETE

**John McCarter<sup>(1)</sup>, Malcolm Chrisp<sup>(1)</sup>, Gerry Starrs<sup>(1)</sup>, Sreejith Nanukuttan<sup>(2)</sup>, Lulu Basheer<sup>(2)</sup> and Muhammed Basheer<sup>(2)</sup>**

(1) Heriot Watt University, School of the Built Environment, Edinburgh, Scotland, U.K.

(2) Queen's University, School of Planning, Architecture and Civil Engineering, Belfast, N. Ireland, U.K.

## Abstract

The concrete cover-zone is a major factor governing the degradation of concrete structures as it provides the only barrier to aggressive agents which initiate corrosion of the reinforcement. Knowledge of the protective qualities of cover-zone concrete is critical 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. To this end, a multi-electrode array was used to study the surface 50mm of concrete specimens thereby allowing a detailed picture of the response of the covercrete to the changing environment. In the current work, CEM I, CEM II/B-V and CEM III/A cements were used and comprised field studies representing a range of exposure conditions.

## 1. INTRODUCTION

The concrete cover-zone (covercrete) provides the only barrier to aggressive agents and hence has a major influence on the deterioration of concrete structures. Knowledge of the protective qualities 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 and compliance with specified design life. Virtually all concrete deterioration processes such as chloride-induced corrosion, freeze-thaw damage, alkali-silica reaction, carbonation and sulphate attack require the presence of water and it is the permeation characteristics of the covercrete that are of interest; strength, per se, is not a requirement although strength is normally associated with durability. Regarding the permeation properties of the covercrete, terms such as diffusion, permeability and sorptivity have been used in this respect.

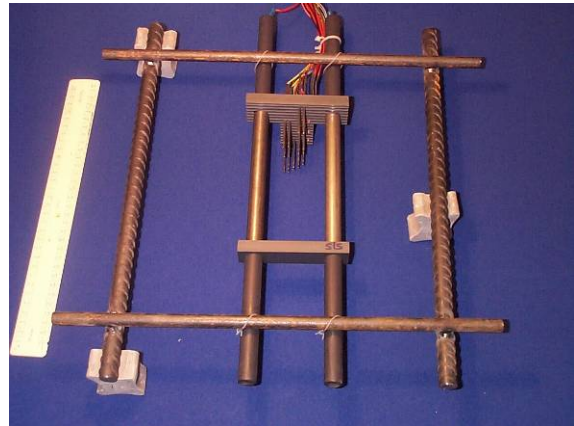
Since the flow of water under a pressure differential (hence permeability) or the movement of ions under a concentration gradient (hence diffusion) is analogous to the flow of current under a potential difference (hence electrical resistance) then the measurement of the electrical properties of concrete could be of practical significance as a simple methodology for assessing cover-zone performance. Furthermore, once passivity is lost, research indicates that the single most important factor affecting the corrosion rate of the reinforcing steel is the electrical conductivity of the surrounding concrete [1].

This paper employs a multi-electrode array embedded within the cover-zone of concrete specimens to allow monitoring of the temporal and spatial variation of electrical conductivity within the cover-zone. This gives a detailed picture of the response of the covercrete to the changing environment.

## 2. EXPERIMENTAL PROGRAMME

### 2.1 Electrical measurements

Resistance measurements were obtained at discrete points within the cover zone of concrete samples by embedding an electrode array in the surface region of reinforced concrete specimens. The array comprised 8 electrode pairs mounted on a plastic former; each electrode consisted of a stainless steel pin (1.2mm in diameter) 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 discrete depths from the exposed surface ranging from 5mm-75mm. The former was secured onto stainless steel bars as shown in Figure 1. The complete module could then be secured to the reinforcement with cable ties.



Four thermistors were also mounted on the former thereby allowing monitoring of the temperature distribution through the covercrete (also required for temperature standardisation of resistance measurements). Prior to installation, the electrode arrays were calibrated in solutions of known conductivity enabling the measured resistance,  $R$  (in ohms), to be converted to conductivity,  $\sigma$  (in Siemens/m), viz,

$$\sigma = \frac{k}{R} \text{ (S/m)} \quad (1)$$

where  $k$  is the calibration constant for the electrode array. An average value of  $k$  was evaluated to give an overall constant for the array.

### 2.2 Materials, Samples and Curing

Table 1 presents the concrete mix details, together with the mean 28-day compressive strength ( $F_{28}$ ) determined on 100mm cubes. These mixes were chosen as they satisfy the requirements for virtually all exposure conditions specified in [2] and [3]. Dredged river gravel and matching fine aggregate was used throughout; the binders comprised ordinary Portland cement (CEM I to EN197-1:2000), ground granulated blast-furnace slag (GGBS to EN15167-1:2006) and pulverised fuel ash (PFA to EN450-1:2005).

Table 1: Concrete mixes (w/b = water-binder ratio)

	CEM I 42.5N	CEM III/A 42.5N	CEM II/B-V 42.5N
OPC (kg/m <sup>3</sup> )	460	270	370
PFA (kg/m <sup>3</sup> )	-	-	160
GGBS (kg/m <sup>3</sup> )	-	180	-
20mm (kg/m <sup>3</sup> )	700	700	695
10mm (kg/m <sup>3</sup> )	350	375	345
Fine (kg/m <sup>3</sup> )	700	745	635
Plasticiser (l/m <sup>3</sup> )	1.84	3.60	2.65
w/b	0.4	0.44	0.39
Slump (mm)	105	140	110
$F_{28}$ (MPa)	70	53	58

Samples took the form of 300×300×200mm (depth) blocks cast in plywood formwork and an array, described above, was placed at the plan centre of each slab. All cabling was colour coded and taken into a watertight reinforced plastic box embedded into the face opposite to the working face. A 37-pin, multi-pole female socket was used to terminate all wires from the electrode array and thermistors. On demoulding, the samples were wrapped with damp hessian and polythene and left in the laboratory (15-20°C) for a period of 7 days. All surfaces, apart from the surface cast against the formwork which was the exposed 'working' surface, were sealed with several coats of an epoxy-based paint to ensure uniaxial moisture movement. A total of 54 blocks (18 per mix) were fabricated.

In parallel with this, nine concrete monoliths - three per mix in Table 1 - of dimensions 2000(high)×400×400mm were fabricated in plywood formwork. The monoliths were lightly reinforced over their full length. An electrode array, similar to that described above, was positioned within the cover-zone of each monolith and secured to main reinforcement at mid-height in all four vertical faces and also at 1.5 and 0.5m above the base of each monolith on the roadside face (see below). All cabling from the arrays was ducted through the base of each monolith to a central communications box.

## 2.3 Exposure Sites

### (a) Marine Site

Specimens were secured in galvanised steel frames and positioned at three environmental exposures: above high-water-level (airborne spray zone: XS1 [2]); just below high-water-level (tidal/splash zone: XS3 [2]), and below mid-tide level ('submerged' zone: XS2 [2,3]). The specimens were distributed as follows: 3 blocks per mix at XS1 exposure, 6 blocks per mix at the XS2 and XS3 exposures (Figure 2). Note: blocks were placed during the month of February.

### (b) Roadside Site

The monoliths were positioned on the grass verge of a single-carriageway trunk road (Figure 3). This is a heavily trafficked road is subjected to regular de-icing during the winter months (XD4 exposure [3]). Note: monoliths were placed during the month of November.



Figure 2: Marine site.



Figure 3: Roadside site

### (c) Urban Site

Specimens (3 blocks per mix) were positioned outside in an open area and exposed to the natural (urban) environment; the exposed face of each specimen was positioned at an angle of approximately 25° in a south facing direction (Figure 4). Blocks were placed during the month of May.

## 2.4 Measurements

A portable (battery operated) data logging system was developed utilising a central logging controller connected to a multiplexing unit. Electrical resistance measurements (at 1kHz) were obtained for the electrode pairs on the array and thermistors. Measurements were converted to conductivity using equation (1) and temperature using the using the Steinhart-Hart equation for the thermistor.

## 3. RESULTS AND DISCUSSION

Due to the considerable amount of data collected for the initial 18-months exposure, only typical results are presented; furthermore, in order to simplify the discussion, the non-dimensional term, normalised-conductivity,  $N_c$ , is introduced and defined as,

$$N_c = \frac{\sigma_t}{\sigma_o} \quad (2)$$

where  $\sigma_o$  is the initial or datum conductivity value measured at a particular electrode depth and  $\sigma_t$  is the respective conductivity at that depth measured at time,  $t$ , after the initial value. In the current work,  $\sigma_o$  represents the conductivity just prior to placement of the test specimen.  $N_c$  values thus give the change in conductivity relative to the initial value at that electrode depth. Due to the considerable amount of data recorded, only a selection of electrode-pairs are presented for illustrative purposes. Note: all conductivity results were standardised to a reference temperature of 20°C.



Figure 4: Urban site

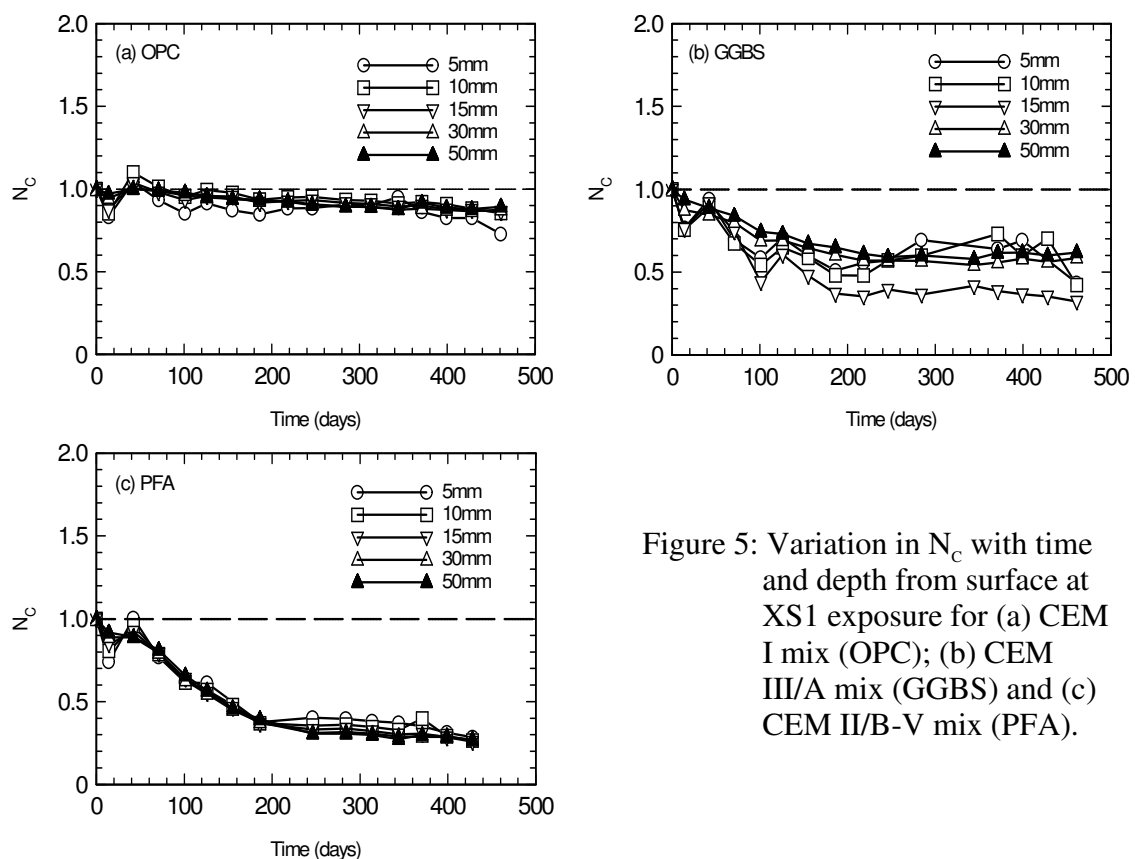


Figure 5: Variation in  $N_c$  with time and depth from surface at XS1 exposure for (a) CEM I mix (OPC); (b) CEM III/A mix (GGBS) and (c) CEM II/B-V mix (PFA).



### 3.1 Test Location : Marine – XS1 exposure

At this location, samples are subjected to chlorides impinging from windborne spray together with local environmental conditions. Initial values (i.e.  $t = 0$ ) were taken just prior to placement of the samples. Considering Figures 5(a)-(c), all curves decrease over the test period although it is evident that the mixes with replacement material display a greater relative reduction than the plain OPC mix. The decrease in conductivity relative to the datum value is attributed to ongoing hydration of the Portland cement and pozzolanic activity associated with the replacement materials.

At this stage, there would appear to be little evidence of ionic ingress into the surface zone or if any, the decrease in conductivity due to microstructural changes are dominating over any possible increase in conductivity due to ionic ingress. The absolute values of conductivity of the matrix (at 20°C) at 50mm (rebar level) at the end of the period presented are, approximately,  $3.3 \times 10^{-4}$  S/cm (3kΩcm) for the OPC mix;  $1.3 \times 10^{-4}$  S/cm (7.7kΩcm) for GGBS and  $1.0 \times 10^{-4}$  S/cm (10kΩcm) for PFA.

### 3.2 Test Location: Marine - XS2 exposure

Samples are positioned below mid-tide level with the result that they are submerged during most of the tidal cycle i.e. at a level where the concrete remains saturated and has no time to dry out. At this location they are subjected to a maximum hydrostatic head of approximately 2.75m at full tide, increasing to approximately 3.75m during spring tides.

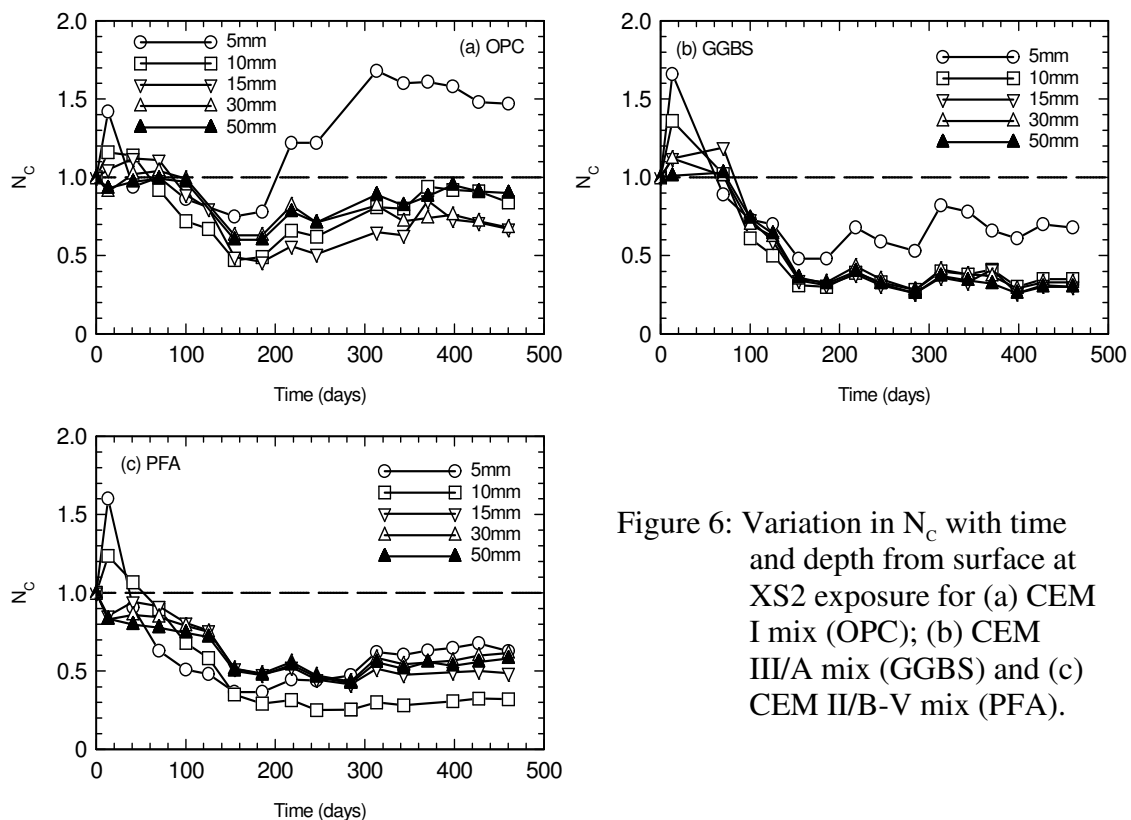


Figure 6: Variation in  $N_c$  with time and depth from surface at XS2 exposure for (a) CEM I mix (OPC); (b) CEM III/A mix (GGBS) and (c) CEM II/B-V mix (PFA).

Figures 6(a)-(c) present the  $N_c$  versus time curves for the test mixes. Over the initial month exposure, these curves increase at the 5mm and 10mm electrode levels for all mixes which is not evident at XS1 exposure (Figure 5). The enhancement in conductivity could indicate penetration of chloride ions into the surface zone under the tidal pressure head. There follows a decrease in conductivity which could be attributed to microstructural changes within the cement matrix resulting from hydration and chloride binding effects. These effects (pore

constriction etc.), which will tend to reduce the conductivity, are dominating over any increase in pore-fluid conductivity resulting from ionic ingress.

One feature which is evident from Figures 6(a) and (b), is the gradual increase in conductivity at the 5mm electrode-level after, approximately, 5-months exposure. The gradual enhancement in  $N_c$  values after this time must result from chloride ingress; this would indicate that sufficient quantities of ions have now reached the vicinity of the 5mm electrode level to increase the pore-water conductivity, thereby increasing the conductivity of the matrix. The values of  $N_c$  continue to increase over the remainder of the period presented indicating increasing ionic concentration within the pore water. It would be anticipated that, with time, as chloride ions penetrate through the cover-zone,  $N_c$  values at each electrode level will increase (in sequence).

The absolute values of conductivity (at 20°C) at a depth of 50mm at the end of the period presented are, approximately,  $2.8 \times 10^{-4}$  S/cm (3.5kΩcm) for the OPC mix,  $1.4 \times 10^{-4}$  S/cm (7.2kΩcm) for GGBS and  $9.0 \times 10^{-5}$  S/cm (11kΩcm) for PFA.

### 3.3 Test Location: Marine - XS3 exposure

The concrete blocks at this location are submerged at high-tide with a maximum head of water above the samples being approximately 0.3m. As with the blocks below mid-tide level (XS2 environment), Figures 7(a)-(c) indicate that these blocks also display an initial increase in  $N_c$  values over the surface 10mm or so, followed by a uniform decrease over the remainder of the period presented. Over the time period presented, the only significant difference between the XS3 and XS2 blocks concerns the plain OPC and GGBS mixes; whereas the  $N_c$  value obtained at the 5mm electrode level on XS2 exposure (Figure 6(a) and (b)) indicates ionic enrichment of the pore water at this depth, this is not present under XS3 exposure.

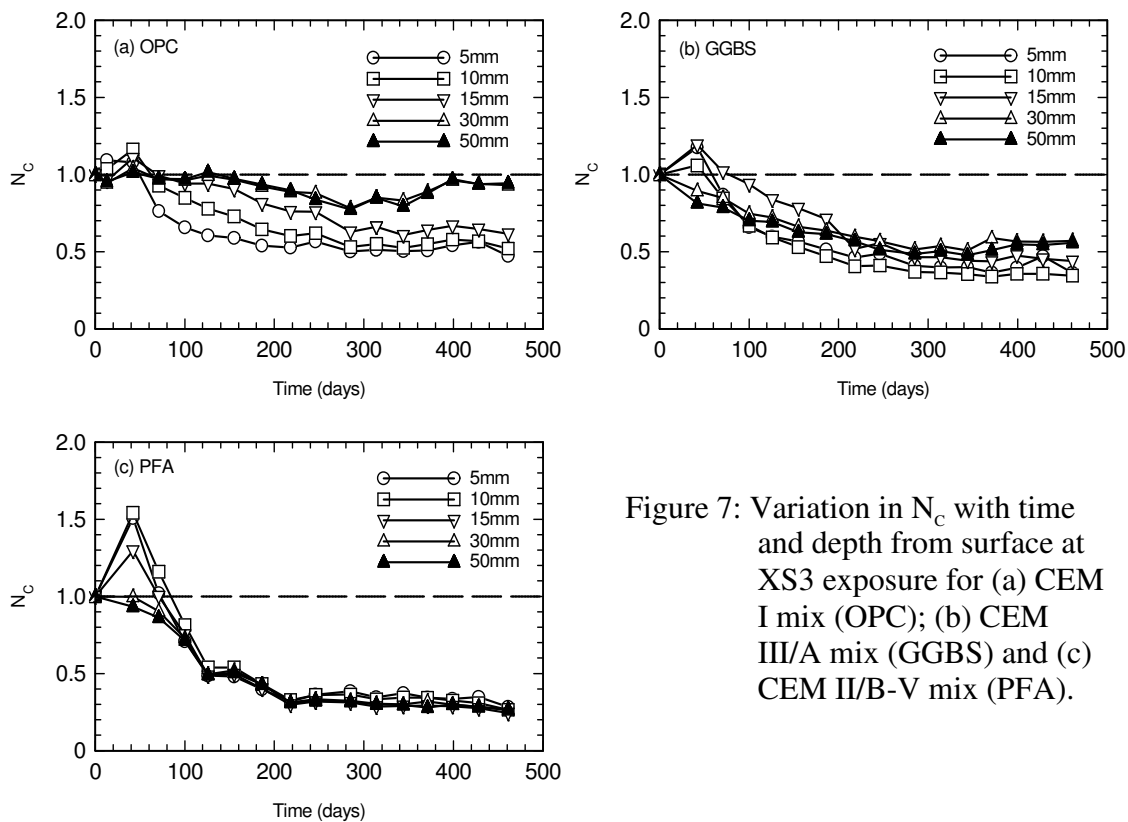


Figure 7: Variation in  $N_c$  with time and depth from surface at XS3 exposure for (a) CEM I mix (OPC); (b) CEM III/A mix (GGBS) and (c) CEM II/B-V mix (PFA).

The absolute values of conductivity (at 20°C) at 50mm at the end of the period presented are, approximately,  $2.8 \times 10^{-4}$  S/cm (3.5kΩcm) for the OPC mix;  $1.3 \times 10^{-4}$  S/cm (7.7kΩcm) for GGBS and  $1.0 \times 10^{-4}$  S/cm (10kΩcm) for PFA.



### 3.4 Test Location: Roadside – XD4 exposure

Figures 8(a)-(c) present the  $N_c$  values at mid-height on the face exposed to traffic spray (see Figure 3) for the initial 6-months exposure. At this stage, these Figures are similar to the XS1 exposure conditions presented in Figure 5. Over the time-scale presented, the decrease in  $N_c$  will reflect microstructural changes due to hydration and pozzolanic reaction.

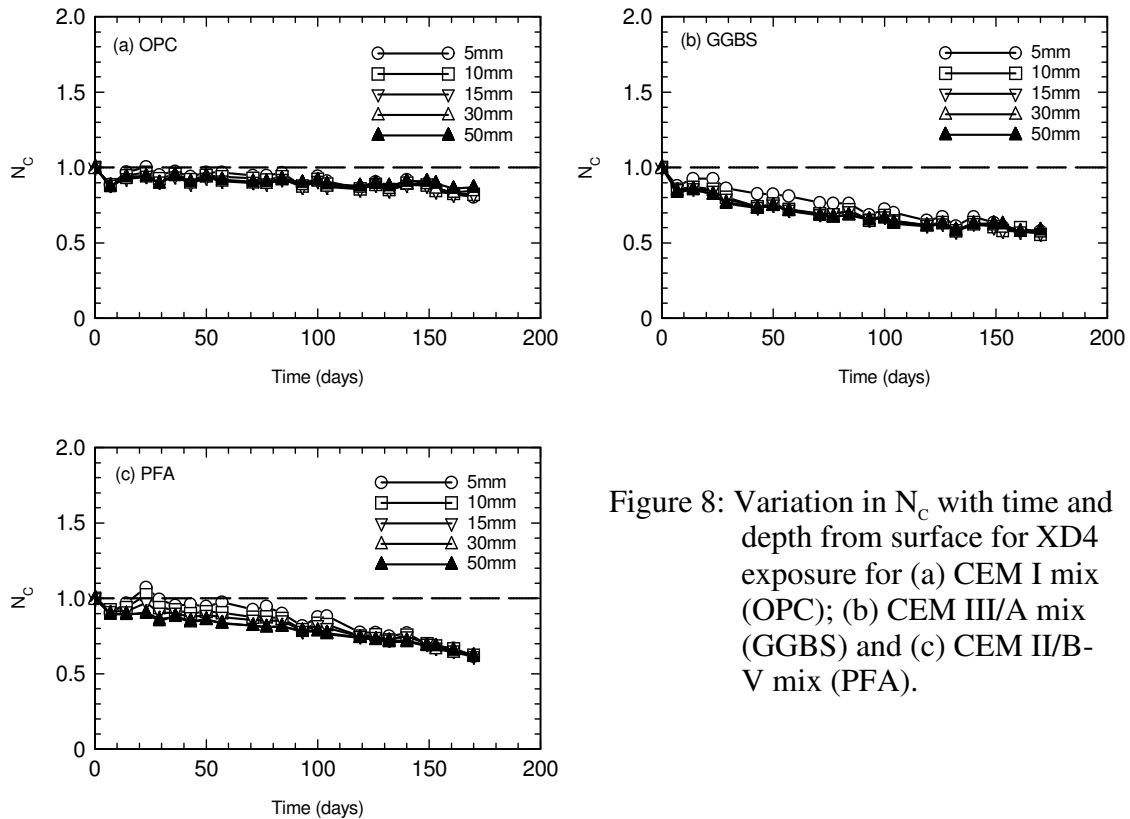


Figure 8: Variation in  $N_c$  with time and depth from surface for XD4 exposure for (a) CEM I mix (OPC); (b) CEM III/A mix (GGBS) and (c) CEM II/B-V mix (PFA).

The absolute values of conductivity (at 20°C) at a depth of 50mm at the end of the period presented (170 days) are, approximately,  $3.2 \times 10^{-4}$  S/cm (3.1kΩcm) for the OPC mix;  $1.3 \times 10^{-4}$  S/cm (4.8kΩcm) for GGBS and  $1.0 \times 10^{-4}$  S/cm (3kΩcm) for PFA.

### 3.5 Test Location – Urban

After the initial 7-days curing, the blocks for the urban site were left in the laboratory for approximately 130-days before being placed outside. Figures 9(a)-(c) present the  $N_c$  versus time response for each mix. Prior to being exposed to the natural environment, electrodes at all positions within the cover display a continual decrease with time - indicative of the combined effect of drying (for the surface electrodes) and on-going hydration/pozzolanic reaction. When the blocks were placed outdoors, rain-water has been absorbed into the covercrete which results in an increase in  $N_c$  values. This is particularly evident over the zone most influenced by the period of drying prior to placement i.e. the surface 30mm. Although obscured by scale, the deeper electrode levels indicate a delayed response to water ingress as the maximum  $N_c$  value is observed approximately 2-3 weeks after being placed outside - this must be as a result of a slower, diffusive movement of water into the cover-zone.

The absolute values of conductivity (at 20°C) at a depth of 50mm (rebar level) at the end of the period presented (480 days) are, approximately,  $2.9 \times 10^{-4}$  S/cm (3.5kΩcm) for the OPC mix;  $1.8 \times 10^{-4}$  S/cm (5.5kΩcm) for GGBS and  $9.0 \times 10^{-5}$  S/cm (11kΩcm) for PFA.

## 4. CONCLUSIONS

The work represents the initial stages in the development electrical property measurements as a testing methodology for assessing the performance of concrete under real exposure conditions. To this end, a multi-electrode array was used to obtain discretized electrical measurements within the cover-zone thereby allowing an integrated assessment of the covercrete. Over the time-scale presented (6-18 months) there was evidence to show that electrical measurements can be interpreted in terms of hydration and pozzolanic activity, drying, and water and ionic ingress; however, longer-term monitoring is required to fully exploit the inter-relationships between electrical property measurements and concrete performance. Work on these aspects are currently in progress.

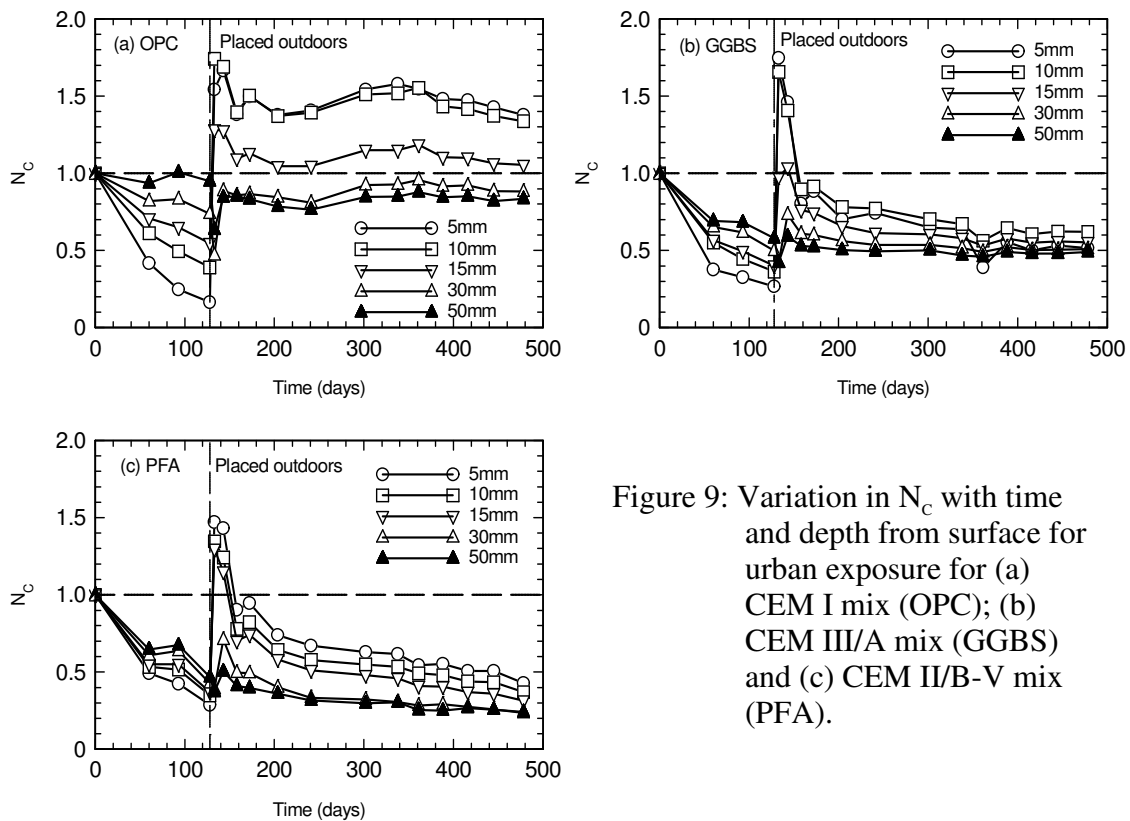


Figure 9: Variation in  $N_c$  with time and depth from surface for urban exposure for (a) CEM I mix (OPC); (b) CEM III/A mix (GGBS) and (c) CEM II/B-V mix (PFA).

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