# Electrical Based Sensors and Remote Monitoring System for Assessing the Corrosion Related Activity in Concrete at Hangzhou Bay Bridge

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**Abstract**. Concrete structures in marine environments are subjected to cyclic wetting and drying, corrosion of reinforcement due to chloride ingress and biological deterioration. In order to assess the quality of concrete and predict the corrosion activity of reinforcing steel in concrete in this environment, it is essential to monitor the concrete continuously right from the construction phase to the end of service life of the structure. In this paper a novel combination of sensor techniques which are integrated in a sensor probe is used to monitor the quality of cover concrete and corrosion of the reinforcement. The integrated sensor probe was embedded in different concrete samples exposed to an aggressive marine environment at the Hangzhou Bay Bridge in China. The sensor probes were connected to a monitoring station, which enabled the access and control of the data remotely from Belfast, UK. The initial data obtained from the monitoring station reflected the early age properties of the concretes and distinct variations in these properties were observed with different concrete types.
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## 1. Introduction

Concrete bridges are generally designed to last for more than 100 years; however in reality due to surrounding aggressive environmental conditions, they deteriorate with time leading to a reduced service life. The deterioration of concrete in extreme environments usually involves movement of aggressive gases and/or liquids from the surrounding environment through the near surface zone concrete, followed by physical and/or chemical changes in their internal structure [1]. Concrete structures in marine environments experience deterioration caused by reinforcement corrosion due to external salts, freeze-thaw, repeated wetting and drying cycles, abrasion due to wave impacts and biological attack. Amongst these deterioration processes corrosion of reinforcement caused by salts from the sea water is one of the most frequently observed damage in marine structures [2]. In general,

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corrosion of reinforcement due to carbonation, chloride ingress and/or leaching accounts for more than 50% of the reported cases in reinforced concrete structures[3]. The environmental factors which influence the deterioration mechanisms are moisture, temperature, wind, carbon dioxide and salts from the sea water. The sudden temperature changes in combination with tidal variations creates wetting and drying cycles at the near surface of concrete, which in turn aggravates the associated deterioration mechanisms.

Although surrounding environmental conditions play a great role in instigating the deterioration processes, their ability to cause deterioration relies on the resistance of the concrete to the deterioration processes. The durability characteristics of concrete can be improved by using supplementary cementitious materials and maintaining proper quality control of materials, concrete manufacturing process and concrete placement. However, in reality one of the prime reasons for durability related issues of structures, which are widely accepted across the civil engineering fraternity is poor workmanship or poor quality control practices. For example, improper curing of concrete *in-situ* can result in shrinkage related cracks at the cover zone, which in turn increases the penetration of salts and other contaminants, eventually leading to corrosion of reinforcement. The cracking resulting from the deterioration processes in concrete is more likely to result in non-serviceability of the structure and, if remained unattended, can eventually lead to its collapse. The current situation in most developed countries is that repair and rehabilitation costs of structures far exceed the total budget for capital development programmes. Moreover, the issue with most structures is not *if* maintenance is required, but *when* – and *where* to schedule it most cost-effectively. Therefore, in order to maintain the serviceability of concrete structures it is essential to monitor the performance of the structure continuously throughout its intended service life. Figure 1 illustrates the usefulness of continuous monitoring of performance of concrete structures in three different stages during the service life of structure, viz. initial stage where material properties of concrete changes, second and crucial stage where initiation of deterioration happens and third stage where propagation of deterioration takes place.

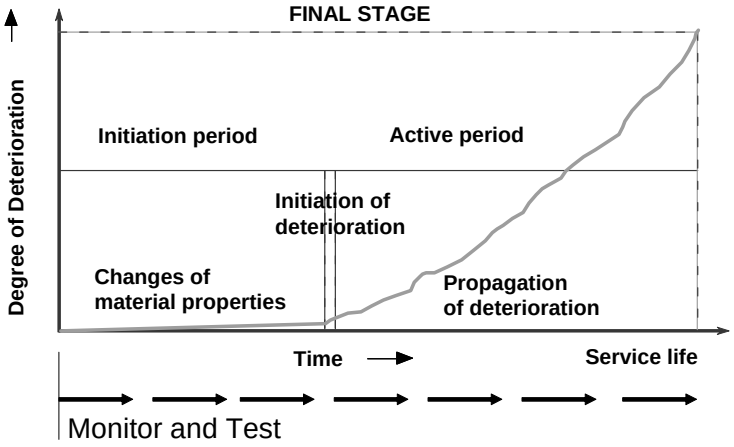



**Fig. 1.** Usefulness of continuous monitoring of structures

As discussed above, deterioration of concrete in marine environment is a complex process involving the rapidly changing environmental factors along with the influence of inherent properties of concrete. In most of the cases researchers have used a specific sensor technique to monitor the associated deterioration process in concrete, which can monitor only the symptoms but not the cause and process of deterioration. For example, anodic ladder sensors are widely used to monitor the level of corrosion at different depths in the cover zone of concrete. However, in order to monitor the cause and process of the corrosion

activity, a combination of sensor techniques are needed to get a better understanding on the factors involved in the deterioration of concrete. The work reported in this paper has used an integrated sensor system consisting of electrical resistance based sensors in combination with corrosion sensors to monitor the properties of concrete at the cover zone. This combination of sensor system will be helpful to monitor the cover zone properties both during the early age and later age of the concrete. The scope of this research work is to study the early age and long-term properties of concrete samples exposed to the marine environment at Hangzhou Bay Bridge, China by continuously monitoring the spatial and temporal changes in electrical resistance, temperature and corrosion current at the cover zone of concrete using the integrated sensor system. In this paper the procedure followed in embedding the sensors in concrete samples, installation of concrete samples at field monitoring station at Hangzhou Bay Bridge, installation of data acquisition and remote data management system and the initial results obtained during the concrete manufacturing and curing phase are described.

## 2. Sensor Probe Design

The integrated sensor system consists of three different sensors, viz. array of 2-pin electrical resistance sensors, temperature sensor and corrosion sensor. The sensor probe, as shown in Fig-2, consists of an array of 2-pin electrical resistance sensors arranged in a staggered manner, electrical resistance based temperature sensors or thermistors and a galvanic cell corrosion sensor.

Fig-2: Sensor probe fixed in a wooden mould before pouring concrete

The staggered emplacement of 2-pin electrical resistance sensors is used to monitor the electrical resistivity or conductivity changes at different depths in the cover zone of concrete. These sensors measure the moisture and ionic movement in building materials in terms of their electrical resistance or dielectric properties of the material which vary with moisture and ionic concentration at a constant temperature. The relationship of electrical resistance with moisture content of building materials was first described by Knowler in 1927, who also explained that unlike in DC based measurements, AC measurements have negligible disturbance caused due to polarisation of electrodes [4]. The electrical property measurement has been used to study the hydration and microstructural evolution of cement based material systems [5–9]. Electrical conduction in concrete occurs primarily due to mobility of ions in the pore solution. Therefore, monitoring the electrical resistivity or conductivity of pore solution during early age of concrete helps in understanding the hydration, setting behaviour and microstructural variations in cement based systems. The

measurement of electrical properties has been used to study various properties in concrete, such as moisture absorption-desorption characteristics [10–12]pozzolanic reactivity of supplementary cementitious materials [13] and transport properties in cover zone of concrete [12][14–16].

The temperature sensors placed at different depths helps in monitoring the thermal gradient in the cover zone of concrete. The temperature data obtained from the concrete can also be used to predict the early age strength of concrete using maturity functions. In addition, the temperature measurements are useful to do temperature corrections on the electrical resistivity data. The corrosion sensor in the integrated sensor probe, as shown in Fig-1, acts as a precursor to the corrosion of reinforcement in concrete structure. Therefore, the corrosion sensor data serves as a warning signal before the main reinforcement in the concrete starts to corrode. The monitoring data obtained from different sensing techniques, if placed together, would provide better information on the material properties of concrete in the cover zone. The history of information gathered from these sensors would be particularly helpful in understanding the key factors involved in the deterioration of concrete structures.

## 3. Data Acquisition and Monitoring System

The monitoring system for the integrated sensor probe needs a robust data acquisition unit which is capable of handling different measurement systems, able to acquire data from multiple sensor probes and sustain the long-term monitoring needs for marine structures. A custom based control and monitoring station was designed to integrate the measurement devices. In addition to monitoring the changes in material properties and the corrosion activity in the cover zone of concrete, a weather station was installed near to the concrete exposure site to monitor the environmental parameters such as temperature, relative humidity and wind speed. The monitoring of concrete cover zone in conjunction with the surrounding weather conditions would help in understanding the influence of environmental factors on the deterioration of concrete. The control unit for the weather station was integrated with the above mentioned custom based monitoring station such that all the sensing techniques were controlled and monitored simultaneously, as shown in the schematic in Fig-3.

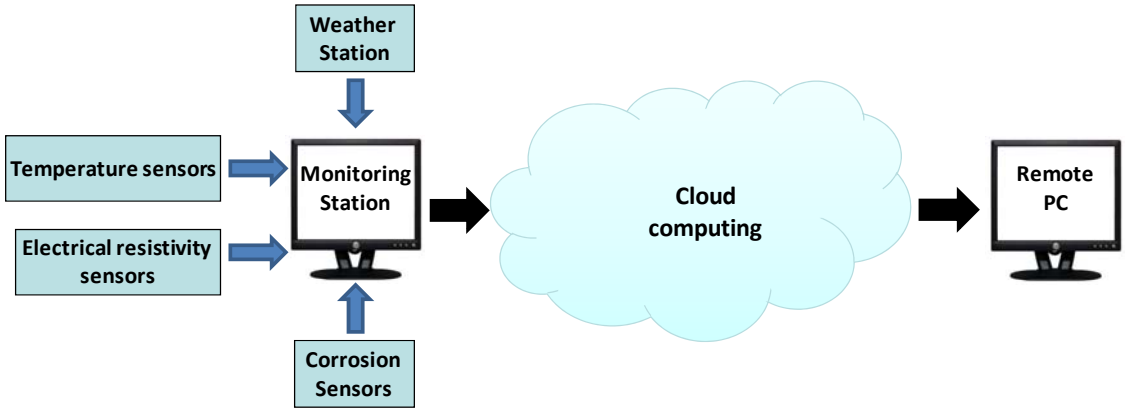



Fig-3: Schematic of the concrete monitoring station

The data obtained from different sensing techniques at the monitoring station was transmitted to a remote PC using cloud computing, as depicted in Fig-3. In addition, using the cloud computing software and the internet, the data could easily be accessed from anywhere in the world.

## 4. Experimental Details

### *4.1 Materials, Sample Preparation and Curing*

In the current experimental programme three different types of concrete were monitored, viz., a High Performance Concrete (HPC) and two grades (C40 and C30) of normal concrete. The mix details of the three concrete types are given in Table-1. The HPC mix used in this experimental programme is similar to the concrete mix used for the piles and pile caps of the Hangzhou Bay Bridge. The C40 mix is similar to that in the pier of the bridge, whereas the C30 mix is a high water-cement ratio mix which is widely used for ordinary constructions in China. Moreover, the C30 concrete was chosen as a low quality mix which would show some deterioration or corrosion in a short period of time in comparison to the other two mixes.

**Table 1** Summary of concrete mixes

| | **HPC** | **C40** | **C30** |
|---|---|---|---|
| W/C | 0.36 | 0.45 | 0.56 |
| PC (kg/m$^3$) | 170 | 439 | 351 |
| GGBS (kg/m$^3$) | 85 | - | - |
| Flyash (kg/m$^3$) | 170 | - | - |
| Fine Aggregate (kg/m$^3$) | 742 | 571 | 650 |
| Coarse Aggregate (kg/m$^3$) | 1024 | 1161 | 1157 |
| Superplasticiser (kg/m$^3$) | 4.25 | - | - |
| Slump (mm) | 100 | 40 | 60 |

The concrete samples took the form of a slab of dimensions 350 x 300 x 150 mm. The sensor probe was fixed at the centre of the inside face of the mould, as shown in Fig-2, by means of a screw drilled through the plywood formwork from the outside. This method of emplacement of the multi-electrode sensors can easily be adapted for monitoring *in-situ* concrete by tying the two arms of the sensor probe as shown in Fig-2 to the main reinforcement at the time of its construction. In this emplacement, the 2-pin electrode array would be in the cover zone of concrete and thus monitor the ingress of moisture or other ionic movements in the cover zone.

The moulds were filled with concrete in three layers of 50mm depth and each layer was compacted using a table vibrator. The concrete samples were de-moulded after 24 hours of casting and then they were covered with a damp hessian cloth. The samples were cured by spraying water from the main supply line on the surface once every day for a period of 4 days, which was similar to the curing regime used for the concrete in the Hangzhou Bay Bridge. After curing the samples in the laboratory for the first 4 days, the samples were wrapped in polythene sheet to avoid any evaporation of moisture and were transported to the marine exposure site at the Hangzhou Bay Bridge. The concrete samples were unwrapped at an age of 5 days whilst they were at the top deck of the marine exposure site and the side faces (350 x 150mm) of the samples were coated with an epoxy paint in 3-layers to restirct the ingress of sea water through the mould finished 350 x 350 mm face of the samples.

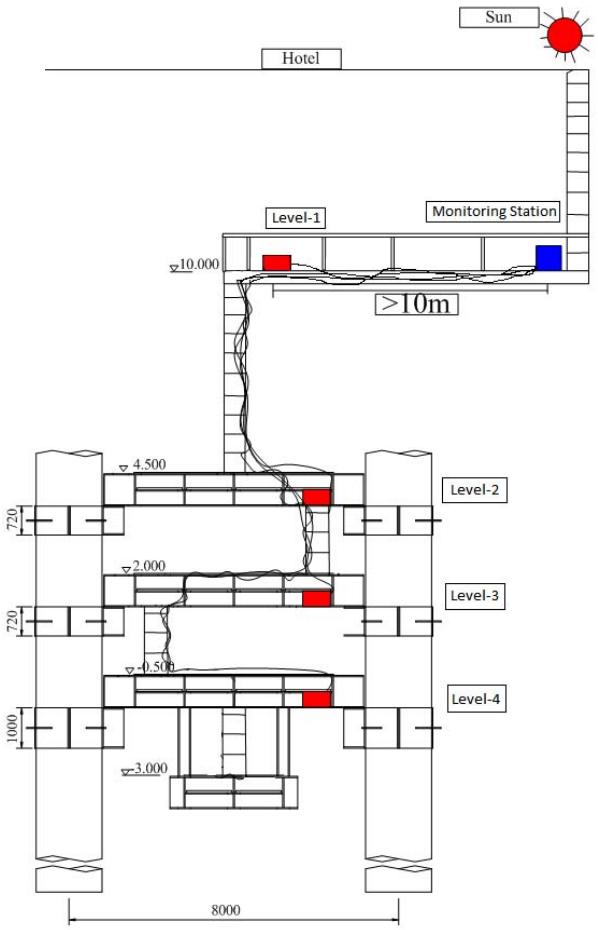
### *4.2 Marine Exposure Site – Location and Conditions*

The Hangzhou Bay Bridge is one of the longest trans-oceanic bridges in the world, which is 35.6 km (22 miles) long and was completed in 2007. The bridge connects the municipalities of Jiaxing and Ningbo at Zhejiang Province in China, as shown in the Fig-4. A service station containing shops and restaurants along with a viewing tower was built at the middle length of the bridge, as shown in the Fig-5. A marine exposure station, shown in

schematic in Fig-6, was constructed at the service station for studying both the performance of concrete and the corrosion of reinforcement in the bridge in this extreme marine environment. The environmental conditions at the bridge are quite extreme, with tidal variations of up to 9m height, which is one of the highest tidal variations in the world, and waves travelling at a speed of 30 kmph along with heavy winds.

Fig-4: Location of Hangzhou Bay Bridge at east coast region of China

Fig-5: Marine exposure site built underneath the service centre at Hangzhou Bay Bridge



Atmospheric zone: above +10.210 m
Splash zone: +1.880〔 +10.210 m
Tide zone: -4.560〔 +1.880 m
Underwater zone: below -4.560 m

Fig-6: Schematic representation and photograph of the marine exposure site at Hangzhou Bay Bridge

The concrete samples embedded with sensors were placed at four different levels, as shown in Fig-6. In each level one slab each of HPC, C40 and C30 concretes were placed. Therefore, the concrete samples at level-1 were in the atmosphere zone, those at level-2 were in the splash zone and those at levels 3 and 4 were in the tidal zone. The concrete samples were fixed by bolting them firmly to the platform so as to avoid any movement or abrasion caused by the waves and tidal variations. The cables coming out from the concrete samples were properly protected by encasing them in flexible PVC pipes and the cables tied to the structure at regular intervals to avoid any movement due to tides. The tail ends of the cables were connected to the monitoring station placed at level-1, as shown in Fig-6. The weather station was placed close to the concrete samples at level-2 in the splash zone to record the temperature and moisture changes in the splash zone. The rain gauge of the weather station records the amount of sea water splash occurring at level-2. The control unit at the monitoring station was programmed to acquire data from different sensing techniques in the integrated sensor probes and transmit the data wirelessly to remote locations using cloud computing.

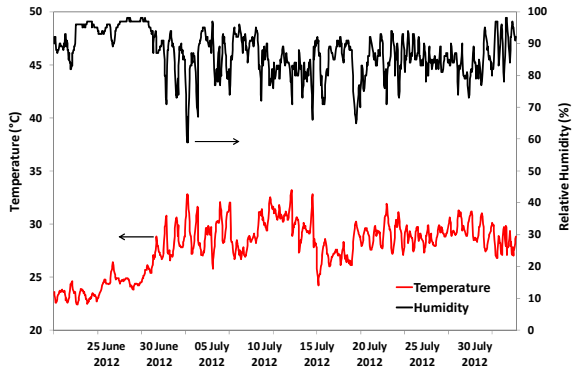



Fig-7a: Variations in Temperature and Humidity at the marine exposure site

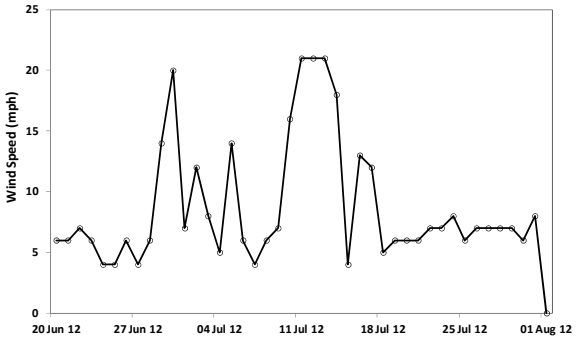



Fig-7b: Variations in daily max. wind speed at the marine exposure site

The weather data obtained from the marine exposure site has been programmed to display the weather conditions live on a web page. The recent data obtained from the weather station placed at the exposure site is shown in Fig- 7a & 7b. It can be observed from the weather monitoring during Jun – Aug'12 period, indicate the cyclic variations in temperature and humidity at the exposure site. The daily maximum wind speed data shown in Fig-7b indicate the severity of the exposure site.

*4.3 Data Acquisition and Analysis*

All the instrumented concrete samples in this study were connected to the monitoring system before concrete was poured into the moulds. The changes in electrical resistance and temperature during the casting and curing phase of concrete were monitored continuously. The data acquisitions from all the concrete samples were programmed to collect at every 5 minutes during the curing period of 4 days in the laboratory. During each data acquisition the electrical resistance values at six different depths, viz. 10, 20, 30, 40, 50 and 80mm from the surface and temperature at four different depths, viz. 10, 30, 50 and 80mm in the cover zone were measured for each concrete sample. As the hydration reaction of concrete changes the electrical resistance and temperature measured at different depths in the concrete, the effectiveness of concrete curing was assessed using this technique.

The electrical resistance measured at different depths using the 2-pin electrode array was converted to electrical resistivity using the following relationship:

$$\rho = c_f R \quad k\Omega\text{-cm} \qquad (1)$$

where ρ is in kΩ-cm, R is in kΩ and $c_f$ is a calibration factor.

The calibration factor was obtained by establishing a relationship between the 4-point electrical resistance and the 2-pin electrical resistance measurements on concrete samples as reported elsewhere by one of the authors [17]. The calibration factor for a similar electrode configuration used in the present work was determined as 2.43 cm [18].

## 5 Results and Discussions

In this investigation three different concrete mixes with different water-binder ratios were tested. The changes in electrical resistivity at different depths with time for the C30 concrete during the first four days of curing are shown in Fig-8a. It may be noted that these data were collected at Belfast from the slabs manufactured in China using the remote monitoring set up described in section 3

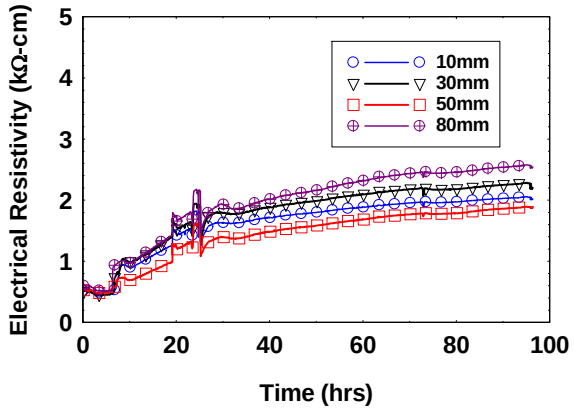



Fig-8a: Changes in electrical resistance at different depths with time for C30 Concrete

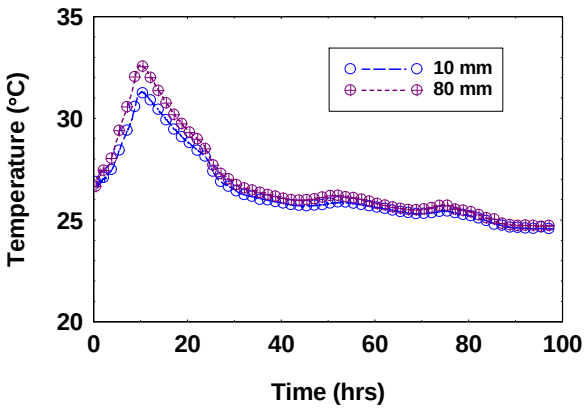



Fig-8b: Changes in temperature at different depths with time for C30 concrete

Based on the trend observed in Fig-8a the graph can be divided into three phases, the first phase is the initial 3 hrs of hydration, the second phase is from 3-24 hrs of hydration and the third phase is from 24-100 hrs of hydration. It can be observed from Fig-8a that during the first phase there is not much change in electrical resistivity values as the ions which conduct electricity between the electrodes are readily available due to the fresh state of concrete. In the second phase as the concrete begins to set and changes into a semi-solid state the resistivity values increase rapidly with time. The changes in resistivity of concrete in the second phase mainly depend on the pore structure formation. In the third phase as the concrete hardens completely the electrical resistivity measured at different depths tends to stabilise with time and the value at which this occurs normally depends on the type of concrete and degree of hydration (i.e. effect of curing).

Fig-8b shows the temperature changes at both 10 mm and 80 mm depths for C30 concrete. It is evident from this figure that the temperature in concrete increased with time for the initial 12 hours due to the exothermic hydration reactions. In addition, the temperature values at 80 mm depth are marginally greater than the temperature measured at 10 mm depth initially, but both were similar after around 2 days. , which is mainly due to the influence of ambient room temperature at shallow depths.

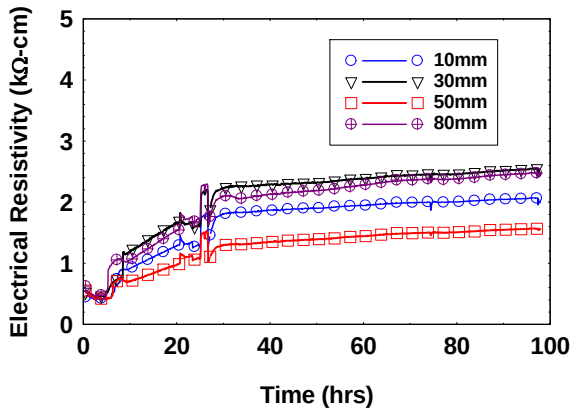



Fig-9a: Changes in electrical resistance at different depths with time for C40 Concrete

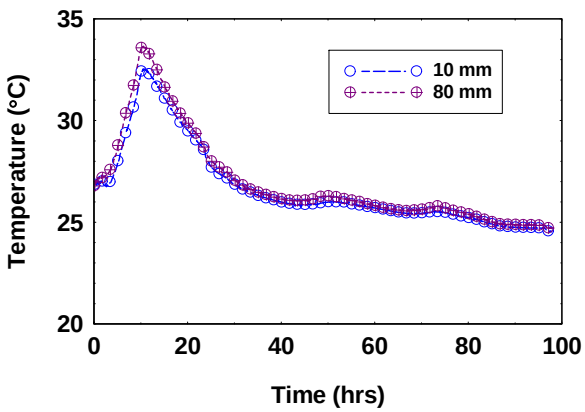



Fig-9b: Changes in temperature at different depths with time for C40 concrete

The changes in electrical resistivity and temperature for the C40 concrete are shown in Fig-9a and 9b respectively. The trend in the changes in resistivity values observed for the C40 concrete is similar to that for the C30 concrete. The rate of changes in resistivity observed in the initial part of the second phase is greater for the C40 concrete when compared to the C30 concrete.

The increase in temperature in Fig. 9b for the C40 concrete is slightly greater than that for the C30 concrete in Fig. 8b. This is considered to be due to increased degree of hydration of cement because the C40 concrete had more cement content compared to the C30 mix.

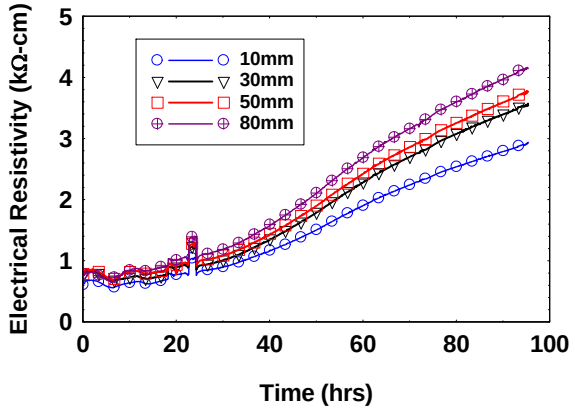



Fig-10a: Changes in electrical resistance at different depths with time for HPC Concrete

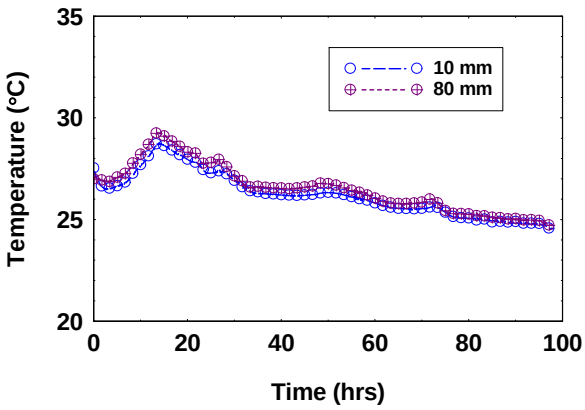



Fig-10b: Changes in temperature at different depths with time for HPC concrete

The resistivity and temperature plots for the HPC concrete are shown in Fig-10a and 10b respectively. The resistivity changes observed for HPC concrete clearly show a distinct feature of prolonged increase in the third phase when comparison to both C30 and C40 concretes. This increase in electrical resistivity at different depths is attributed to the slow pozzolanic reaction and better pore structure in the HPC concrete. Moreover, the rapid increase of resistivity in the second phase is not observed in the case of the HPC concrete due to the slow pozzolanic reaction of fly ash and GGBS in the concrete.

The increase in temperature for the HPC concrete as shown in Fig-10b is low in comparison to that for both C30 and C40 concretes. This is attributed to the low heat of hydration of HPC containing supplementary cementitious materials in the concrete mix.

The electrical resistivity values for fresh concrete were generally low (Figs. 8a, 9a and 10a) due to the high conduction through dissolved ions in the fresh state of concretes. As the cement in the concrete hydrates with time the concrete hardens slowly depending on

the cement content, water-binder ratio and the content of the supplementary cementitious materials in the concrete mix, which in-turn increases the electrical resistivity measured at different depths in the concrete. At the hardened phase of concrete the electrical resistivity values depends on the pore structure formation, pore connectivity and constituents of the pore solution in the concrete. Both the temperature and the electrical resistivity data obtained from the sensors were useful to differentiate the mixes. It is hoped that these sensors will be invaluable to assess the onset of corrosion of steel embedded in the three different concrete mixes for the samples exposed at the Hangzhou Bay bridge.

## 6. Conclusions

The work presented highlights the importance of integrated sensor systems for assessing the properties of concrete in the cover zone and predicting the remaining service life. An advanced remote monitoring station was developed and instrumented at the Hangzhou bay bridge in China, which enabled monitoring and access of information on concrete performance remotely from Belfast, UK. In this research work the external environmental conditions at the exposure site was monitored in conjunction with the internal properties in the cover zone of concrete. This work also highlights the importance of measuring electrical properties and temperature of the cover zone of concrete, which can be used to assess the effectiveness of curing, rate of hydration and pore structure formation during the early ages of concrete. The investigation carried out in monitoring spatial distribution of electrical resistivity and temperature with time for different concrete mixes has led to the following conclusions:

- The electrical resistivity changes monitored for the C30, C40 and HPC concretes have shown three different phases during their early ages of hydration. The initial phase lasted until the concretes stiffened, the second phase coincided with the development of pore structure as a result of hydration during 3-24 hours and the third phase was for hydration beyond 24 hours. The temperature sensors in the integrated sensor system were able to monitor the heat evolution due to the hydration reactions in the three different concretes.
- There was prolonged increase in electrical resistivity observed for the HPC concrete, which was absent for both C30 and C40 concretes. This is considered to be due to the influence of slow pozzolanic reaction of the supplementary cementitious materials, viz. fly ash and GGBS in the HPC mix. The temperature data for the HPC mix clearly showed lower heat of hydration, which is considered to be due to the delayed reaction caused by the presence of the supplementary cementitious materials in the HPC mix.

## 7. Acknowledgements

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