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TECHNICAL REPORT

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TR 6.4

SMART STRUCTURAL MATERIALS WITH PERMANENT MONITORING SYSTEM FOR CONCRETE: NOVEL SENSORS FOR MONITORING THE DURABILITY OF CONCRETE STRUCTURES

ATLANTIC AREA
Transnational Programme
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SMART STRUCTURAL MATERIALS WITH PERMANENT MONITORING SYSTEM FOR CONCRETE: NOVEL SENSORS FOR MONITORING THE DURABILITY OF CONCRETE STRUCTURES

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NOTE:

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented.

PREFACE

This Technical Report (TR) is one of a series of technical reports which were prepared inside the DURATINET project working Group WG-A 6 “Smart & green structural materials” concerning new materials or systems which could improve the durability of structures and to reduce the carbon footprint associated to the construction and maintenance of structures.

In this TR sensors for monitoring the durability of concrete structures based on electrical and optical fibre technology are presented and some results reported for different kind of sensors. The monitoring of concrete durability by the application of a combination of different type of embedded sensors can ensure that a proper maintenance strategy could be developed for the diagnosis of faults and incipient failures and to schedule maintenance effort most effectively and huge sums currently spent on repair and rehabilitation works should be saved and the possibility of catastrophic failure minimized.

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DURATINET project approved by the Atlantic Area Programme and co-financed by ERDF

CONTRACT Nº: 2008-1/049

ACRONYM: DURATINET

PROJECT TITLE: Durable Transport Infrastructure in the Atlantic Area Network

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CONTENTS

1 Introduction 1
2 Monitoring concrete durability 2
2.1 Embeddable sensors for monitoring concrete 2
3 Electrical sensors 4
3.1 Electrical resistance based covercrete sensors 4
3.1.1 Monitoring moisture changes in concrete 5
3.1.2 Monitoring carbonation in concrete 7
3.1.3 Monitoring cover concrete in marine environment 8
3.2. Electrical based corrosion sensors 9
3.2.1 Monitoring using reference electrodes 9
3.2.2 Sensor based on macro-cell measurements 11
3.2.3 Sensors based on Linear Polarisation Resistance (LPR) 11
3.2.4 Electrical based chloride sensors 12
4 Novel fibre optic sensor systems for monitoring concrete durability 14
4.1 Sensors based on Fibre Bragg Grating (FBG) technique 14
4.1.1 Strain monitoring in reinforcement 15
4.1.2 FBG Humidity probe 16
4.1.3 Corrosion monitoring using FBG sensors 17
4.2 Fibre optic pH monitoring in concrete 19
4.3 Fibre optic chloride sensor 20
5 Conclusions 22
6 References 23

1 Introduction

Reinforced concrete structures, such as bridges, roads, tunnels, dams and buildings, are a major part of civil infrastructure in the world. It can be said that reinforced concrete as a composite construction material is distinguished for its very long service life in comparison to other building materials. However, in reality when these concrete structures are subjected to extreme environmental conditions they tend to deteriorate rather in an alarming rate. Therefore, maintaining the durability of concrete structures for intended service life is of great concern to civil engineers. The deterioration of porous building materials usually involves movement of aggressive gases and/or liquids from the surrounding environment into the near surface zone of the porous materials, followed by physical and/or chemical changes in their internal structure (Basheer and Nolan, 2001). For example, in some extreme environments salts, moisture and carbon dioxide penetrate into concrete cover and eventually lead to corrosion of embedded steel reinforcement. The movement of these aggressive substances occurs due to differentials in humidity, ionic concentration, pressure and temperature within the microstructure of concrete. The damage caused by these deteriorations is of either physical or chemical in nature or even both. The chemical deterioration can be caused by external attack that mainly occurs through the action of aggressive ions, such as chlorides, sulphates and other salts, originating from sub surface soil, penetration of carbon dioxide from atmosphere resulting in the carbonation of concrete and the action of acid rain. The physical deterioration effects can arise due to changes in thermal expansion of water in concrete as a result of the 'freeze-thaw' process, stresses in pore structure caused by crystallisation of salts and fatigue caused by thermal stresses. 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. 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.

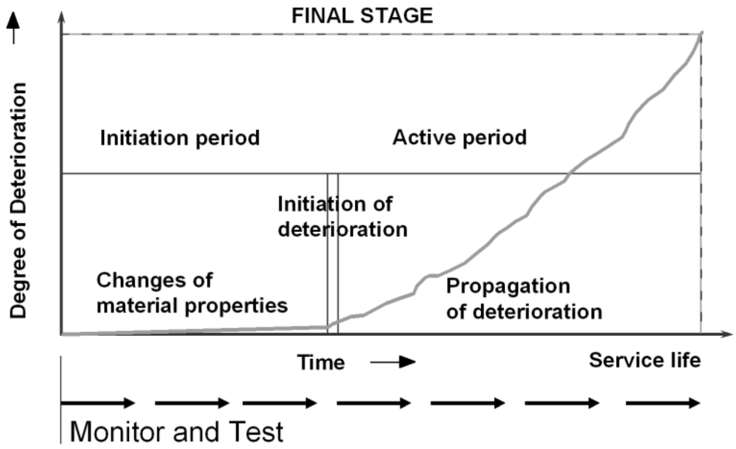

Fig.1.Usefulness of continuous monitoring of structures

2 Monitoring concrete durability

The conventional approach for diagnosis of deterioration process was to perform chemical analysis using cores cut from the concrete structure. In the case of corrosion related deterioration the concrete was assessed by measuring the depth of carbonation and chloride profile of cover concrete. In addition, there are specialised non-destructive and partially-destructive techniques available to assess the condition of concrete depending on the type of deterioration involved. However, these techniques can only provide information on condition of concrete on that particular day and time of testing and it would be an expensive task to test frequently the condition of concrete. A better understanding on the deterioration process and hence the condition of concrete can only be attained by studying the history of temporal and seasonal changes that takes place in the cover zone of concrete. Smart structures – structures incorporating in their design sensor elements and actuating devices which not only diagnose a problem but affect a solution to the problem – represent one approach for the diagnosis of faults and incipient failures and to schedule maintenance effort most effectively and at optimum cost, minimising the possibility of catastrophic failure.

2.1 Embeddable sensors for monitoring concrete

For effective monitoring of concrete structures the sensors should have the ability to be embedded in concrete, robust enough to withstand the harsh environments in concrete, small enough to be placed in the cover zone of concrete, good sensitivity and repeatability, cost effective and easy to log and store the data. Embeddable corrosion sensors have great significance in durability monitoring because deterioration caused due to corrosion of reinforcement is widely recognised as a major reason among durability related failure of concrete structures. One amongst the well known corrosion sensor is Schie□l's ladder, in which the penetration of corrosion front is monitored by comparing the potential between each rod of the ladder with a reference electrode [Schie□l and Raupach, 1992]. Further different design of sensors with discrete electrodes have been developed based on electrical properties of concrete/steel [Bäßler et. al, 2000; Montemor et. al, 2006; Legat, 2007] and other electro-chemical sensors with reference electrodes [Atkins et al, 1996, Montemor et. al, 2006, Muralidharan, 2007], which demonstrated the capability to monitor the corrosion front in cover concrete. The sensor system developed by McCarter [McCarter et. al, 1992, 1995] monitors the spatial distribution of electrical conductivity within the cover zone of concrete, which is based on the inter-relationship between electrical properties of concrete with ionic diffusion and corrosion dynamics. Novel optical fibre sensors have also been used to monitor different factors contributing to the durability of concrete [Fuhr et. al, 1996, Laferriere et. al, 2008]. Fibre optic chloride sensors have been developed for monitoring chloride threshold for reinforcement corrosion. These sensors are based on different techniques such as fluorescence based sensor [Fuhr et. al, 1996; Laferriere et al, 2008]. Several humidity sensing techniques have also been reported with fibre optics in recent years. Some of the sensors are based on techniques such as Fibre Long Period Grating [Healy, 2003], Fibre Bragg Grating [Yeo et. al, 2005; Pascal, 2002; Srinivasan et. al, 2009] and Fibre Bragg grating with Fabry-Perot interferometry [Arregui et. al, 1999]. Fibre optic pH sensor based on sol-gel entrapped indicator has been developed for monitoring pH changes due to carbonation of concrete [Dong et al, 2007].

As many factors contribute to the durability of concrete structures, for their effective monitoring an integrated system containing combination of sensors is needed, which can provide temporal and seasonal variations in quality of concrete cover and reinforcement. In the following sections the development of novel sensors based on electrical resistance and fibre optic techniques used for monitoring physical and chemical parameters, such as temperature, strain, moisture, pH and chloride, which are crucial to predict the durability of concrete structures.

3 Electrical sensors

3.1 Electrical resistance based covercrete sensors

Electrical resistance based 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. This 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 (Knowler, 1927).

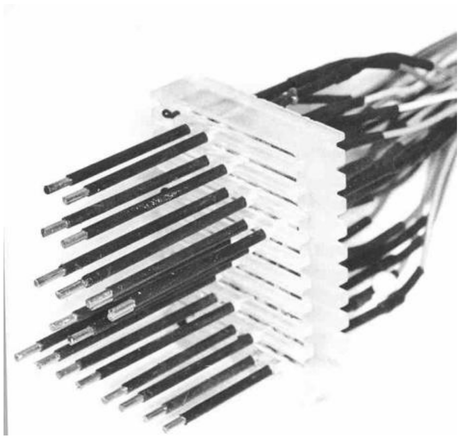

Fig. 2. Covercrete electrode array

The primary function of the Covercrete Electrode Array developed by McCarter et al at Heriot-Watt University, Edinburgh [McCarter et. al, 1992, 1995] is to provide real-time data on the condition of the covercrete and the spatial distribution of cover-zone properties. The electrode array consists of 10 pairs of stainless steel electrodes (1.6mm dia.) placed at different depths, sleeved with heat shrink tubes so as to expose a length of 5mm at the tip as shown in Fig. 2. The pairs of electrodes are mounted parallel to the suction surface enabling the electrical properties of the concrete measurements (resistance in this instance) to be obtained at 10 discrete points through a depth of 50mm in the cover concrete. Thermistors are also mounted on the former thereby enabling temperature profiles to be obtained.

The conductance (inverse of the resistance) measured across the pairs of electrodes can be presented in the following four ways:

i) variation of as-measured conductivity (in Siemens/m, S/m) as a function of time, t, for each electrode position on the sensor;

ii) variation of conductivity measurements obtained in i) which have been standardised to the reference temperature (20°C) thereby allowing changes in conductivity due to temperature to be minimised. This is particularly important for site measurements;

iii) variation of normalised conductivity using the values in ii) above where the normalised conductivity, NC, is defined as,

$$NC = \sigma t / \sigma o \qquad \text{[Eq. 1]}$$

σt is the standardised conductivity measured at a particular electrode position on the sensor at time, t, and σo is the conductivity measured at that respective electrode position taken at a datum point in time. NC values thus allow relative changes in conductivity to be studied. Data can also be normalised by the conductivity obtained at a depth of 50mm, i.e.

$$N^*C = \sigma t / \sigma t{,}50 \qquad \text{[Eq. 2]}$$

Where σt is as defined above, and $\sigma t{,}50$ and is the value of conductivity across the electrode pair positioned at 50mm at time, t. The 50mm electrode level was chosen as the response at this depth was found to remain relatively unaffected by drying and wetting action at the surface.

iv) variation in as-measured conductivity (or any of formalisms above) as a function of depth through the cover, thereby allowing electrical profiles through the covercrete to be studied.

The above formalisms could be applied for the resistances obtained as well. That is, instead of the normalised conductivity, it is possible to determine the normalised resistivity.

3.1.1 Monitoring moisture changes in concrete

As discussed earlier the durability of cover concrete has been associated with water transport properties, such as sorptivity and permeability. Sorptivity is recognised as a fundamental hydraulic property that offers sensitive means of exploring capillary absorption. The covercrete array sensors are primarily used to study the water sorptivity of different concrete mixes as an indicator of their durability [McCarter et. al, 1992]. In Fig. 3, as water moves into the zone of influence of the electric field, the electrical resistance decreases due to the increased conductance in the pore solution [McCarter et. al, 1995].

The profile of normalised resistivity for a normal Portland cement concrete in a standard capillary rise test is shown in Fig. 4. As can be seen from this figure, the resistance ratio decreased with time for all the electrode pairs, but the most affected electrodes were those nearer to the exposure face. The derivative of the normalised resistivity values provides time of arrival of moisture front at different depths in the cover zone of concrete. The covercrete array sensors can also be used to study different other moisture related properties and processes in cover zone, such as the degree of saturation and its variation, effective porosity and influence of cyclic wetting and drying on the pore structure.

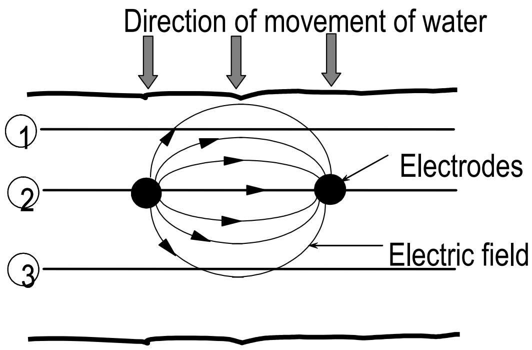

Fig. 3.The spread of electric field between embedded electrodes [based on McCarter et. al, 1995]

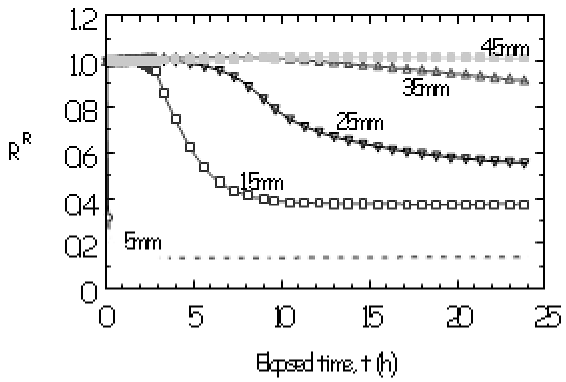

Fig .4. Resistivity ratio for electrode pairs at different depths from the exposure face of a concrete block [Basheer et. al, 2005]

In a separate laboratory based research the applicability of electrical resistance technique to monitor drying and conditioning of concrete samples were studied in conjunction with relative humidity measurements using a commercial probe. The relative humidity (RH) measured at different depths after drying of concrete samples for 4 weeks at 40ºC indicated that the RH nearer to the surface decreased at a higher rate than that of the interior concrete, as shown in Fig. 5. However, during the conditioning process where the specimens after drying were wrapped in a polythene sheet and kept in an oven at 40ºC, the RH was redistributed internally and a uniform value of 55% RH was obtained all along the depth of the concrete.

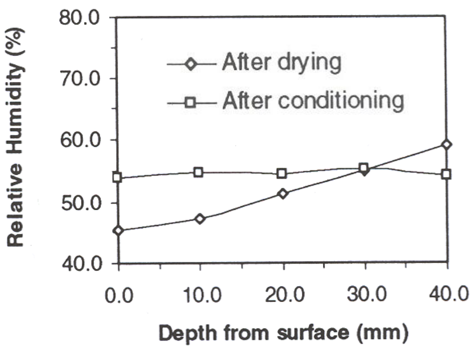

Fig. 5. Typical RH profile after drying and conditioning for 375kg/m3 mix (Target RH 55%)

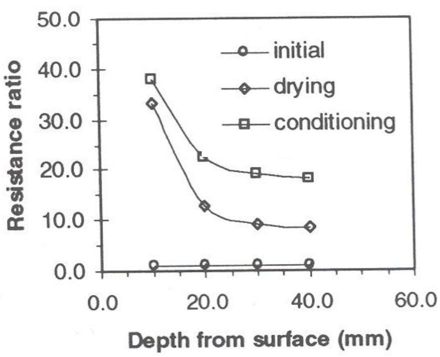

Fig. 6. Typical resistance ratio profiles due to drying and conditioning for 375kg/m3 mixes (Target RH 55%)

The resistance ratio at four different depths were measured during the process of drying and conditioning at three different periods, viz. before the start of drying, after drying and end of the conditioning regime. During the course of the drying regime, the resistance ratio changed from a constant value at all depths to a profile with increased value nearer to the surface (Fig. 6), attributed due to the decrease in RH. However, during the conditioning of the specimens to redistribute the moisture, the internal resistance continued to increase at a non-uniform manner, as can be seen in Fig. 6. This is probably due to continued improvement of the pore structure as a result of the continued hydration of cement in addition to the redistribution of the internal moisture in specimens.

3.1.2 Monitoring carbonation in concrete

Russell [1999] studied the applicability of electrical resistance sensors in monitoring changes in properties of concrete during an accelerated carbonation test regime. Fig. 7 shows the depth of carbonation of specimens after a six-week accelerated carbonation test regime on different concrete samples with varying W/C ratios and constant cement content of 375kg/m3. Although the resistance ratio varied during the carbonation period, the exact nature of this variation is not clear for all the water-cement ratios presented in Fig. 8. As stated before, there were the continued changes in microstructure during the carbonation period, which should have increased the resistance ratio throughout the test duration. However, the release of moisture during the carbonation process could have an opposite effect on the resistance ratio. Overall, it is not possible to draw any significant conclusions from the resistance ratio graphs, which means that the resistance measurement alone may not be useful to follow the carbonation profiles within concrete.

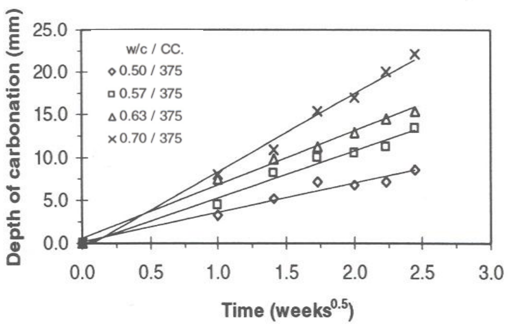

Fig. 7. Typical depth of carbonation during the six-week carbonation period for 375kg/m3 mixers (55% RH specimens)

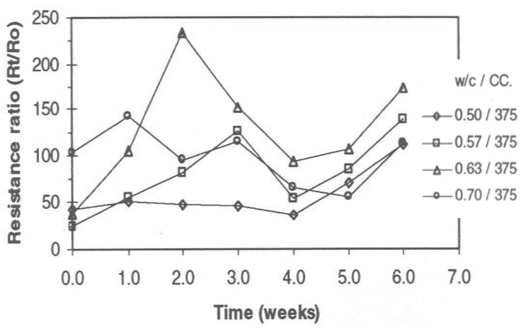

Fig. 8. Resistance ratio at 10mm depth during the six-week carbonation period for 375kg/m3 mixes (55% RH specimens)

3.1.3 Monitoring cover concrete in marine environment

Figure 9 shows concrete blocks exposed to a marine environment site in Scotland. Figures 10 to 12 show the conductivity values of Ground Granulated Blastfurnace Slag (ggbs) admixed concrete blocks exposed to this environment. In Fig. 10 the as measured conductivity values, after correcting for the temperature variations, are presented. In this case, the conductivity decreased with time, i.e. the resistivity increased with time, unlike the data in Fig. 8. This indicates that not only the ggbs concrete provided resistance to the chloride ingress in the marine environment, but also the continued pozzolanic reaction had resulted in an improvement in its electrical resistance.

The change in normalised conductivity in relation to the initial value can be seen in Fig. 11 and that of the electrode pairs at different depths with respect to the conductivity of the electrode pair at 50mm is presented in Fig. 12. A comparison of Figs. 10, 11 and 12 would suggest that different types of information can be obtained from different representations of the measured conductivity values. In Fig. 11, it can be seen that there is a continuous decrease in conductivity at all the different depths and Fig. 12 would suggest that the decrease in conductivity was higher for the electrode pairs at both 5 and 10mm depths, presumably due to the fact that small amounts of chlorides (or water) might have penetrated up to these depths and improved the microstructure of the concrete.

Fig. 9. Concrete blocks exposed to the marine environment in Dornach, Scotland

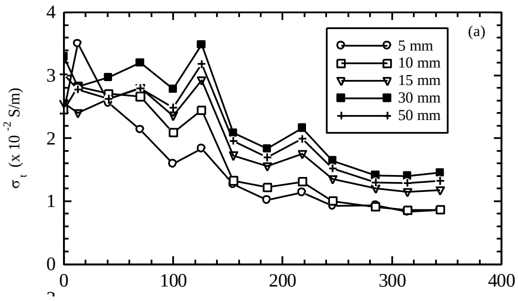

Fig. 10. Change of conductivity of ggbs concrete in the marine environment

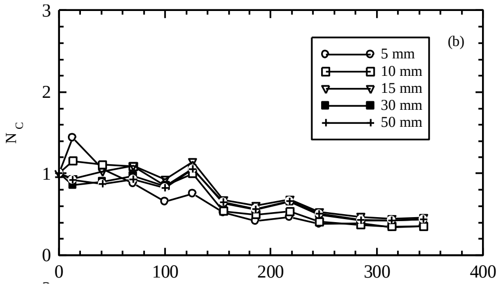

Fig. 11. Normalised conductivity (with reference to the start value) in the marine environment

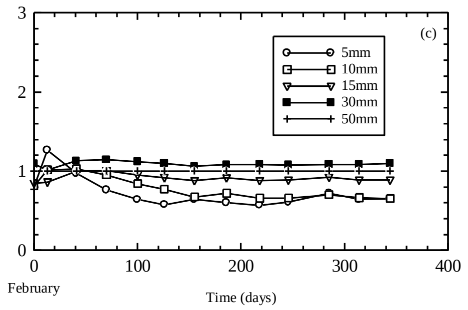

Fig. 12. Normalised conductivity (with reference to the 50mm depth data) in the marine environment

3.2. Electrical based corrosion sensors

3.2.1 Monitoring using reference electrodes

As discussed earlier, monitoring the rate of deterioration of structures due to corrosion has a great importance because it is the most commonly occurring form of deterioration in reinforced concrete structures. Monitoring the corrosion activity of reinforcement using sensors gives more precise information of the actual corrosion process, time of initiation of corrosion and if used with combination of other sensors can provide better knowledge on the factors influencing the corrosion process.

Amongst the many techniques available, the measurement of electrochemical potential of steel reinforcement in concrete using reference electrodes is a popularly used technique to assess the corrosion activity. This is based on the principle that electrochemical potential of a metal in a solution is measured in relative to a fixed and known electrode potential set up by a standard reference electrode in the same electrolyte. The basic design of reference electrode is shown in Fig. 13. The reference electrode is embedded in the cover concrete at the close vicinity of reinforcement as shown in Fig. 14 to measure changes in electrochemical potential during the corrosion process. In electrochemical measurements the most commonly used reference electrodes are Copper/Copper Sulphate ($Cu/CuSO_4$) reference electrode, Standard Calomel Electrode (SCE) and Silver/Silver Chloride (Ag/AgCl) reference electrode. In the case of SCE's the metal is Hg (Mercury) in a sparingly soluble salt of Hg_2Cl_2 (Mercury chloride) contained in a saturated solution of KCl, whereas in Ag/AgCl reference electrode a varying concentrations of KCl solutions ranging from 0.1 M to saturated solution are used [Myrdal, 2007]. Therefore, due to the variability of reference electrodes, care should be taken in translating the potential obtained by any type of reference electrode to corrosion activity of steel. The potentials of various reference electrodes in reference to normal hydrogen electrode (NHE) and the criteria for assessing corrosion condition based on potential values are shown in Table 1.

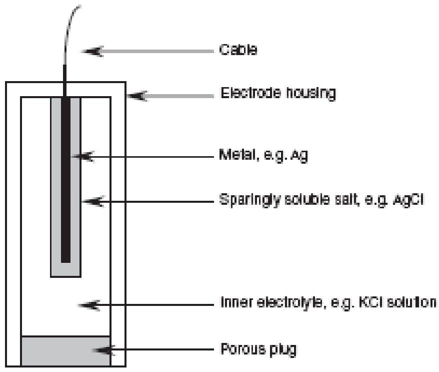

Fig. 13.Reference electrode design [Myrdal, 2007]

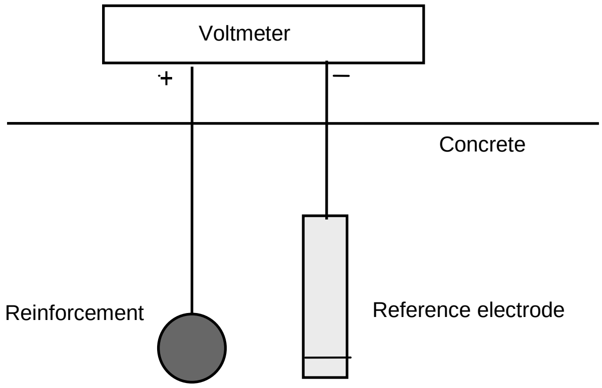

Fig. 14. Schematic showing electrochemical potential measurement in concrete [adapted from COST 521, 2003]

Table 1. ASTM specification for corrosion of steel in concrete for different standard electrodes [Broomfield, 2007; ASTM C876]

Copper/copper sulphate	Silver/silver chloride/ 1.0M KCL	Normal hydrogen electrode (NHE)	Standard Calomel Electrode (SCE)	Corrosion condition
>-200 mV	>-100 mV	+120 mV	>-80 mV	Low (10% risk of corrosion)
-200 to -350 mV	-100 to -250 mV	+120 to -30 mV	-80 to -230 mV	Intermediate corrosion risk
<-350 mV	<-250 mV	-30 mV	<-230 mV	High (>90% risk of corrosion)
<-500 mV	<-400 mV	-180 mV	<-380 mV	Severe corrosion

In order to embed the reference electrode in concrete the design of the sensor should have the capability to withstand the impact of fresh concrete in new construction and should be robust to sustain the aggressive environment experienced in cover concrete. The SCE's are not normally used for embedment in concrete as it contains a liquid metal and makes it difficult to manufacture a robust design. Ag/AgCl reference electrode has been widely used by embedding them in concrete, which can be manufactured with rugged design and has reasonably good design life of 15 years [Myrdal, 2007]. Manganese dioxide (MnO2) in alkaline solution is another reference electrode that is commercially available and has been embedded in concrete. Muralidharan manufactured an embeddable MnO2 sensor in a three layer design that consists of a porous hydrated cement paste as bottom layer, alkaline slurry as middle layer and MnO2 powder as top layer [Muralidharan, 2007]. This embeddable MnO2 electrode sensor has shown better stability and reliability in both simulated concrete pore solution and in concrete. In some other work manganese dioxide was also tried as pH and humidity sensors [Telli et. al, 2000; Xu et. al, 1998]. Therefore, the potential measured using this sensor is influenced by pH of the pore solution. The measurement of potential values in concrete using reference electrode varies depending on moisture, pH and chloride concentration at the vicinity of the embedded reference electrode.

3.2.2 Sensor based on macro-cell measurements

In this type of sensor a galvanic cell is created which consists of an anode and a cathode (Fig. 15). Electrical current between the anode and cathode is measured which is proportional to the dissolution of iron at the anode due to corrosion activity. The change in the galvanic current gives the corrosion rate of the anodic steel in the host material. This type of sensor has been used quite widely since around 1990 to monitor corrosion activity in concrete.

The most popular anodic-ladder system has been developed by Schie□l [Schie□l and Raupach, 1992] which has been used to monitor corrosion risk in new structures. This consists of series of carbon-steel anode mounted at different depths from the surface of concrete as shown in Fig. 15. Stainless steel or activated titanium is used as the cathode, which is placed in the concrete near the anode. The ingress of chloride or carbonation front through the cover concrete reaches the individual carbon-steel bars in the ladder causing depassivation and increases the current between anode and cathode. The sensor arrangement is used as a corrosion precursor sensor that provides information on time of corrosion of main reinforcement and critical depth of corrosion. Another anodic ladder system has been used in bridge decks and tunnels which consist of mild-steel anode and stainless steel cathode [Raupach and Schie□l, 1997]. This sensor system has widely been used in concrete structures in Europe and is commercially available in the market [Sensortec, 2005].

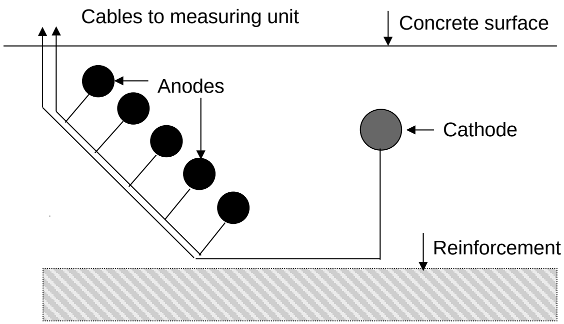

Fig. 14. Schematic of Anode-Ladder system in cover concrete [adapted from COST 521, 2003]

3.2.3 Sensors based on Linear Polarisation Resistance (LPR)

The Linear Polarisation Resistance technique is used to measure the rate of corrosion of steel reinforcement in concrete. The principle of linear polarisation technique relies on applying a small electric current and measuring the shift in corrosion potential, thus monitoring the active corrosion in steel. In this system mild steel is used as working electrode that should represent the actual reinforcement in concrete, an auxiliary electrode is used to pass the current and a reference electrode or half-cell is used to measure the potential and its changes. The LPR method with guard ring probe for surface based measurements is an established non-destructive technique to measure the corrosion rate of reinforcement in concrete structures. The criteria for interpretation of damage due to corrosion using corrosion rate measurements are shown in Table 2.

Table 2. Typical interpretation of corrosion rate measurements [adapted from COST 521, 2003]

Corrosion rate ($\mu A/cm^2$)	Attack penetration (loss of section of reinforcing bar) (μm/year)	Corrosion level
<0.1	<1	Negligible
0.1 to 0.5	1 to 5	Low
0.5 to 1	5 to 10	Moderate
>1	>10	High

Sensor probes based on LPR technique have been used to measure the corrosion rate of reinforcement in new structures [Broomfield et. al, 2002; Broomfield, 2007; Duffo and Farina, 2009]. The embeddable LPR sensor developed by Broomfield et al, 2002, as shown in Fig. 16, consists of a mild steel bar of known area as working electrode to measure corrosion rate of steel in cover concrete and additional facility to connect to the main reinforcement in the structure to measure the actual corrosion rate [Broomfield, 2007]. Another sensor system [Duffo and Farina, 2009] consists of combination of sensors to measure corrosion rate, temperature, chloride ion concentration and electrical resistivity in concrete structures, as shown in Fig. 17. The set of sensors contained in a porous mortar is used as a corrosion probe to monitor various parameters involved in the corrosion process of reinforcement in concrete structures.

3.2.4 Electrical based chloride sensors

In recent years considerable research attention has been focussed on developing chloride ion sensors for monitoring concrete structures. A well known chloride ion sensor is through electrical measurements based on silver electrodes with silver chloride (AgCl) coating, which functions due to the soluble nature of AgCl (Atkins et al, 1996; Montemor et. al, 2006). This method suffers from disadvantages, such as limited longevity of Ag/AgCl electrodes, influence of temperature and pH on measurements and influence of other ions like bromide ions present in sea water (Atkins et. al, 2001). These electrodes are insensitive to low chloride ion concentration and another major disadvantage of this method is that Ag/AgCl electrodes must be wet for allowing the chloride ions to be mobile at the time of measurement.

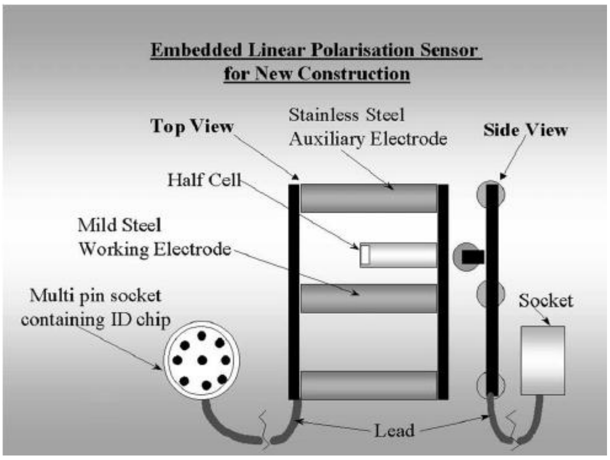

Fig. 16. LPR sensor for corrosion monitoring in new structures [Broomfield et. al, 2002]

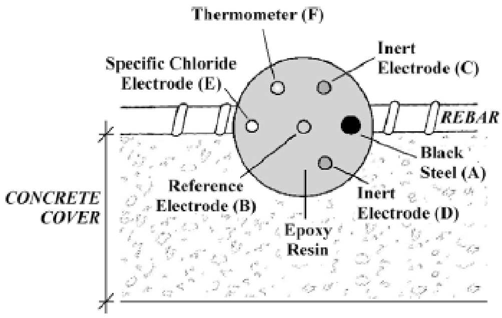

Fig. 17. Schematic of multiple sensor probe in concrete [Duffo and Farina, 2009]

A combined chloride and resistivity sensor element has been developed and extensively used in concrete structures for monitoring free chloride concentrations and electrical resistivity [COST 509, 1997]. In this sensor the potential of embedded chloride sensor is measured relative to MnO2 reference electrode [Bertolini, 2004]. Another patented chloride ion sensor technique includes a pair of electrodes and a polymer film imprinted for chloride ions under alkaline conditions [Murray et al, 2005]. The polymer film (methylpyrrole) is deposited on at least one electrode of the pair, which allows measurements in wet or dry media. The electrical conductivity of polymer film depends on the amount of chloride ions taken up by the film. This technique has the advantage of measuring chloride ion concentration both in wet and dry media and at high pH range. The major drawback in this technique is that the sensor is non reversible and thus it could only measure the accumulation of chloride ions.

4 Novel fibre optic sensor systems for monitoring concrete durability

The use of fibre optic sensors (FOS) has been increasing in the field of structural health monitoring during the past few years. Optical fibre based sensors offer numerous advantages in comparison to the conventional electrical methods of monitoring. The main advantages of fibre optic sensors are: they are extremely small; lightweight; robust; corrosion resistant; immune to electro-magnetic interference; can be multiplexed and have high sensitivity and hence suits well for harsh environments encountered in concrete structures. Amongst fibre optic sensor technology different sensor techniques are available for monitoring civil engineering structures. They can be classified based on the characteristics of light, such as intensity, wavelength, phase and polarisation which get affected by the sensing parameter. FOS can also be classified as point based sensors (Fibre Bragg grating sensors), Long-gauge sensors (quasi-distributed sensors) and distributed sensors [Glisic and Inaudi, 2008]. Fibre optic sensors has the ability to monitor high temperature -200ºC to 800ºC with silica core and 1500ºC with a sapphire core [Li et al, 2004]. The quasi-distributed and distributed sensors can monitor host parameters in large civil structures at multiple locations [Inaudi and Glisic, 2007]. Fibre optic sensors have the capability to measure a wide range of parameters relevant to health monitoring of civil structures, viz. physical parameters, such as strain, inclination, pressure, forces, accelerations and vibrations; temperature and chemical parameters, such as humidity, pH, oxygen and chloride concentration. Amongst these ranges of sensors the most crucial parameters for durability monitoring of concrete are temperature, humidity, strain, pH and chloride content of concrete and corrosion of rebar. The development and application of these sensors in concrete are explained in this section.

4.1 Sensors based on Fibre Bragg Grating (FBG) technique

Fibre Bragg Grating (FBG) based sensors are popularly used in structural health monitoring of construction materials due to their better sensitivity to strain and temperature [Slowik et. al, 1998; Glisic and Inaudi, 2008; Measures, 2001]. Moreover, the small dimensions of FBG's can be utilised as "micro-sensors" for monitoring minute variations in pore structure of concrete which are important in understanding durability aspects of concrete. The manufacturing process, developments and application of these sensors are well documented in major books and book series [Glisic and Inaudi, 2008; Measures, 2001; Grattan and Meggitt, 2000; Lopez-Higuera, 2002; Udd, 1995].

The FBG sensor consists of narrow gratings which are formed by creating a periodical refractive index modulation in a photosensitive optical fibre using the phase mask writing technique. The grating acts as a narrow-band reflection filter that reflects a particular wavelength of light depending on the spacing/period of grating. The reflected Bragg wavelength (λB) is given by Eq. 3:

$$\lambda_B = 2n_{eff(core)}\Lambda \qquad \text{[Eq. 3]}$$

where neff(core) is the effective refractive index of the core and Λ is the grating period. The fractional wavelength change due to strain induced on the sensor is given by equation 4:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-Pe)\varepsilon + [(1-Pe)\alpha + \xi]\Delta T \qquad \text{[Eq. 4]}$$

where Pe is the photoelastic constant of the fibre (typical value for silica fibre is 0.22), is the strain induced on the fibre, ε is the fibre thermal expansion coefficient and α is the fibre-thermo-optic coefficient. Therefore, the shift in wavelength of light can be attributed to either strain or change in temperature based on the established calibration relationship between wavelength vs. strain and wavelength vs. temperature. In this technique a single interrogator can simultaneously monitor multiple FBG sensors at different locations in a single fibre. Therefore, a single fibre containing multiple FBG sensors can be laid all along the host structure and can get point based measurements of stain and temperature at different locations. However, due to the inter-relationship between wavelength-strain-temperature, the strain measurements have to be compensated for temperature changes and at the same time the temperature sensor has to be isolated from strain.

4.1.1 Strain monitoring in reinforcement

A comparative study between the performance of Electrical Resistance Strain Gauges (ERSGs) and FBG sensors has been performed by monitoring induced strain on a steel rod under standard test conditions. The test arrangement showing the extensometer and FBG sensor attached to the steel rod is given in Fig. 18. Figure 19 shows the Load vs. Strain measurements made on the rod and compares performance of FBG sensor with ERSG and extensometer measurements. The standard deviation of strain measurements in relative to extensometer is 96 με for ERSG and 64 με for FBG sensor. That is, the FBG sensor gives a lower value of standard deviation in comparison to ERSG sensor and has good correlation with the extensometer. This gives the confidence for using FBG based strain sensors in structural monitoring applications.

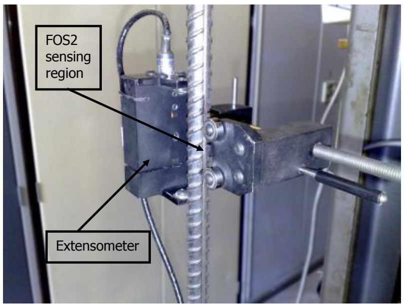

Fig. 19. Steel bar with FBG sensor attached along with extensometer

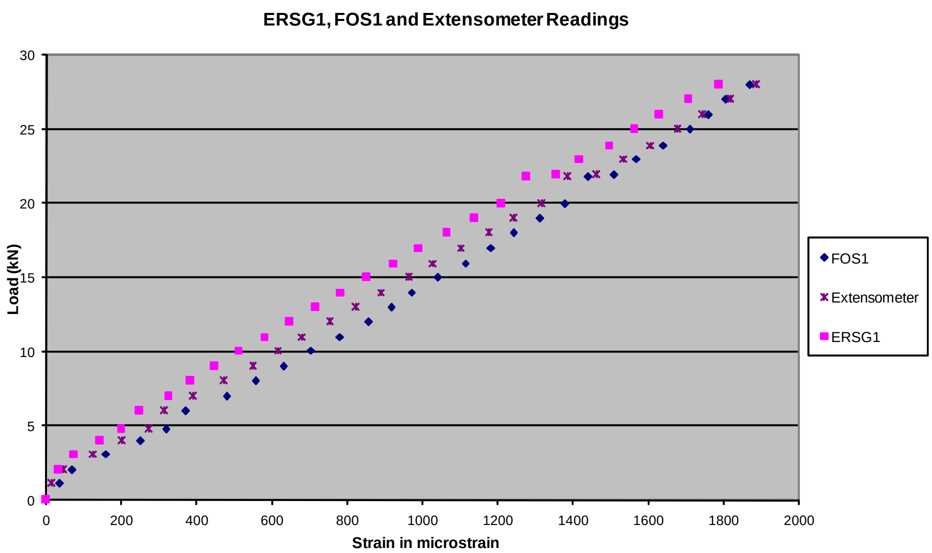

Fig. 20. Comparison of results from FOS1(FBG), ERSG1 and extensometer showing change in strain ($\mu\varepsilon$) as a function of load (kN)

4.1.2 FBG Humidity probe

The FBG sensor has also been used for measuring moisture or relative humidity [Giaccari et. al, 2001]. The principle used in this work relies on coating a moisture sensitive polymer on a FBG sensor which swells or expands with increase in moisture, thereby induces a strain effect on the FBG. Therefore, the relative humidity level is given by optically measuring the shift in wavelength caused by the expansion of moisture sensitive coating on the Bragg grating. A linear relationship is obtained between relative humidity and wavelength through calibration at standard humidity levels [Yeo et. al, 2005]. Further research on this concept has improved the sensitivity and reliability of the technique [Yeo et. al, 2005; Pascal, 2002; Laytor, 2002]. The FBG sensor fabrication, procedures for coating moisture sensitive material and optimum coating thickness for better sensitivity and response time have been described by some of the authors in previous publications [For instance, Yeo et al, 2005 a & b].

The humidity sensor probe in its basic design was used to monitor moisture changes in concrete by placing the probe in a hole drilled in concrete, as shown in Figs. 20 and 21. The moisture ingress in concrete sample was monitored by measuring the changes in Bragg wavelength, as shown in Fig. 21. Following the success of this system, an embeddable design of fibre optic relative humidity (RH) probe was developed for monitoring moisture in concrete structures, as shown in Fig. 22 [Srinivasan et. al, 2009]. The embeddable RH probe consists of both temperature and moisture sensor based on FBG technology. The sensors were encased in a polycarbonate tube with a sensing cavity volume of 30mm3 and a porous cap of 20μm pore size placed at the tip in order to prevent the bare sensor grating from contamination by the cement paste, possible impact by aggregates in fresh concrete and for long-term monitoring of hardened concrete. The performance of the RH probe was tested in a concrete slab made with water-cement ratio of 0.55, placed at a depth of 30 mm from surface and subjected to a capillary rise test. The results of the capillary rise test indicated that the fibre optic RH probe had monitored the moisture ingress with a sudden change in RH values, as shown in Fig. 23. The RH probe specially tailored for applications in concrete structures can be used for monitoring cover concrete and can provide seasonal variations in RH that could be useful in understanding the durability of concrete.

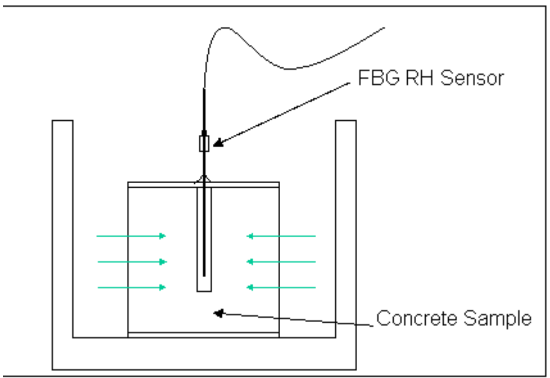

Fig. 20. The fibre optic humidity probe inserted centrally to monitor ingress of water with time

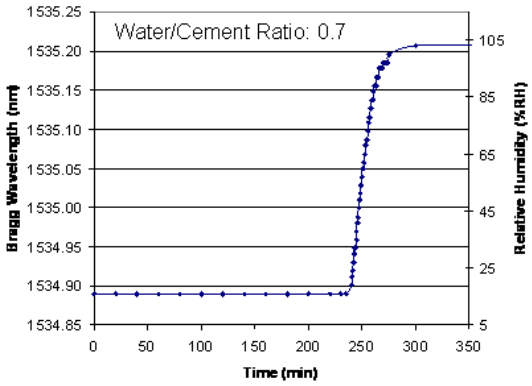

Fig. 21. The change in Bragg wavelength due to ingress of water in concrete sample

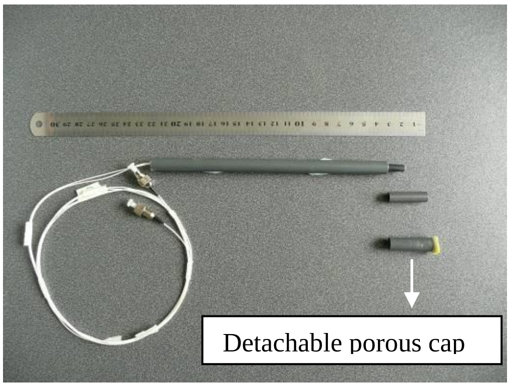

Fig. 22. Embeddable FOS-RH probe with FBG based humidity and temperature sensor

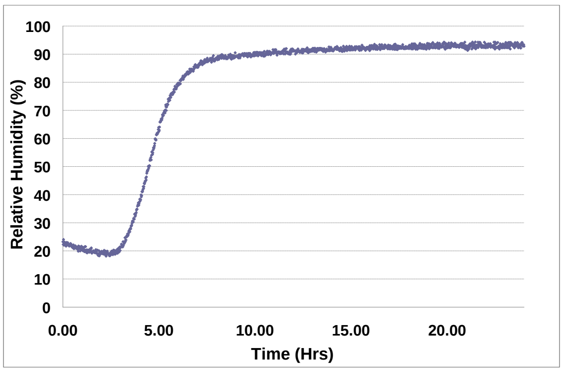

Fig. 23. Change in RH with time monitored in concrete in a capillary rise test using Fibre optic RH probe

4.1.3 Corrosion monitoring using FBG sensors

Monitoring corrosion activity of reinforcement has a great value in durability monitoring of concrete structures. Optical fibre sensors for monitoring steel corrosion based on different sensing techniques have been developed by many researchers [Leung et. Al, 2008; Grattan et. al, 2007; Singh et. al, 2000; Fuhr and Huston, 1998].

Grattan et al, [2007], have studied the use of FBG sensors in monitoring corrosion of rebar in concrete samples. The technique is based on the principle that as the reinforcement corrodes, the products of corrosion occupy a larger space resulting in stresses in the transition layer between the rebar and the concrete. The stress caused due to corrosion in the transition layer is monitored using FBG strain sensors which are attached to the reinforcement, one on the top face of the bar and another on the bottom face. In this work the performance of the FBG strain sensors was compared with ERSGs embedded in separate concrete slabs subjected to similar conditions of accelerated corrosion. The strain measurement with time from the two types of sensors during the on-set of corrosion is shown in Fig. 24. The results indicate that the FBG strain sensors have successfully responded to the stresses caused by the on-set of corrosion of reinforcement in concrete samples. The strain resulting from the corrosion can be distinguished from a standard strain, for example due to loading, by the fact that once the load is removed the strain will reduce, but with corrosion this will remain until the excess volume has reduced. Therefore, with the use of FBG strain sensors it is possible to know if the reinforcement in a structure has corroded or not, although the actual corrosion rates may not be determined.

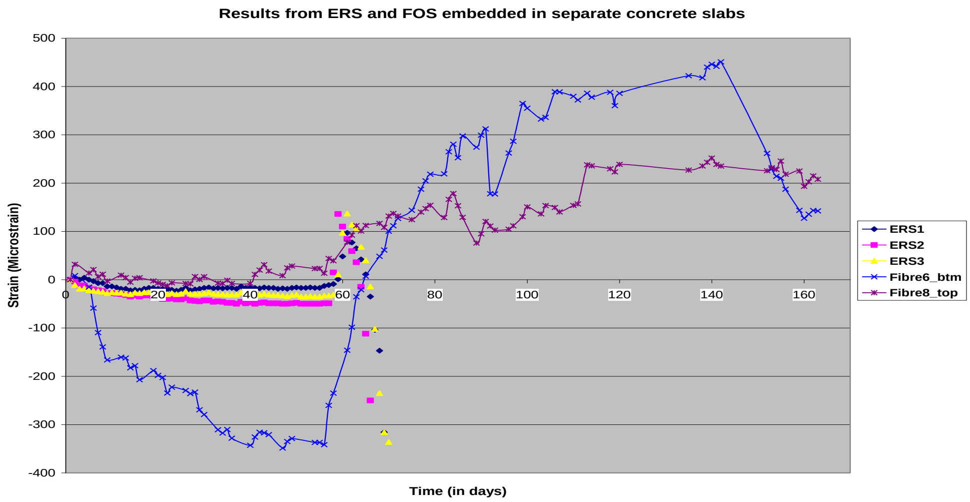

Fig. 24.Strain measurements from ERSGs and FBG sensors during accelerated corrosion test [Grattan et. al, 2007]

Another notable corrosion sensor was developed by Leung et. al 2008, which is based on monitoring reflected light in an optical fibre with tip of the fibre coated with a thin iron film. As corrosion occurs, the thickness of the coating decreases and subsequently the intensity of reflected signal drops, as depicted in Fig. 25. The fibre sensor embedded in concrete subjected to salt ponding tests and the loss in reflectivity of light in fibre optic sensor was compared with standard macro cell current measurements, as shown in Fig. 26.

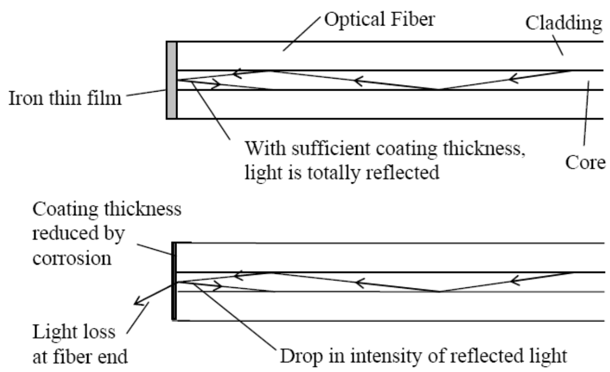

Fig. 25.Corrosion sensing using iron thin film coating[Leung et. al 2008]

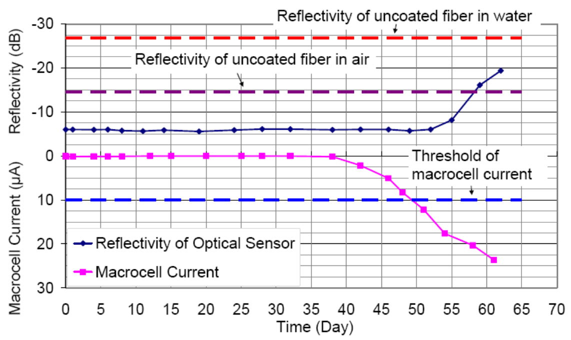

Fig. 26. The performance of fibre optic sensor in corrosion monitoring compared with macrocell current measurements [Leung et. al 2008]

4.2 Fibre optic pH monitoring in concrete

The requirement for a suitable pH monitoring method that is non-destructive and provides timely information on the likelihood of corrosion of reinforcement due to carbonation of the concrete has led to the development of fibre optic pH sensor using different techniques. These techniques are based on optical or spectroscopic properties, such as absorbance, reflectance, fluorescence and refractive index [Korostynska et. al, 2007; Xie et. al, 2004; Staneva and Betcheva, 2007].

Sol-gel based pH sensor has been a potential sensor for applications in concrete [Xie et. al 2004; Basheer et. al 2004, 2005; McPolin, 2005]. The first report of the use of a sol-gel based approach to a fibre optic pH sensor was demonstrated by Badini et. al, [1989]. This sensor concept relies on the absorption properties of the sol gel which is linearly related to the concentration of the sample. The pH probe was constructed by coating sol-gel containing cresol-red indicator dye (pH range 8-13) onto the plastic clad silica fibre of core diameter of 600µm. A Tungsten halogen lamp was used as light source and a small portable spectrometer was used to analyse the reflected light. The spectrometer, light source and the pH probe are shown in Fig. 27. In this work the sol-gel based pH probe was compared with commercial disk based (porous matrix impregnated with indicator dye) fibre optic probe, by embedding the probe in mortar samples. The pH measurements obtained using sol-gel based pH probe is shown in Fig. 28. The results indicated that the sol-gel probe reached a stable pH at approximately 30 minutes after it was embedded in mortar. The pH values obtained by sol-gel probe correlated with apparent pH profile obtained by the digestion method [McPolin, 2005; McPolin et. al, 2007].

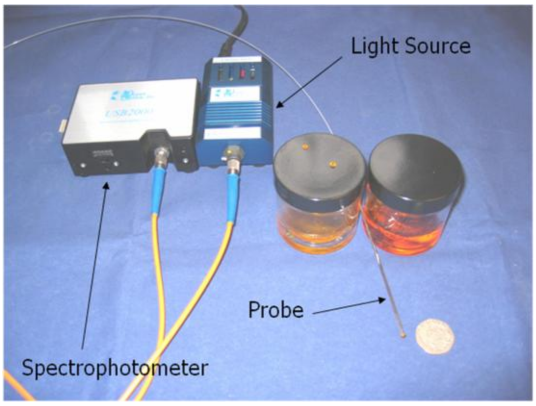

Fig. 27. Fibre optic pH sensor set-up

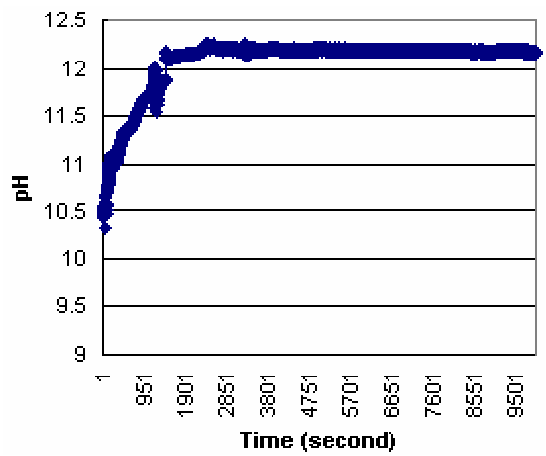

Fig. 28. pH change with time in mortar sample using sol-gel based pH probe

4.3 Fibre optic chloride sensor

Fibre optic chloride sensors reported in literature are based on different techniques, such as fluorescence based [Fuhr et. al, 1996], absorption based and reflection based [Cosentino et. al, 1995] and changes in refractive index based [Tang et. al, 2007]. Most of these methods are non reversible based measurements and some have limited longevity at high pH ranges. In the work reported by Cosentino et al, [1995] the sensor layer was exposed to silver nitrate (AgNO3), which reacted with NaCl forming a white precipitate of AgCl and this change in colour was sensed and related to concentration of chlorides. Reflective and absorption based sensors were also reported in the same paper using silver chromate powder. These methods are non reversible and hence the sensors could be used for monitoring cumulative chloride concentration reaching the level of sensors. Another similar work was reported by Fuhr et. al, [1997] where the technique was modified by using dichloroflouroscein dye which changes colour from pink to milky white depending on the concentration of positive charged silver ions in AgNO3 solution. These sensors were embedded in various bridge deck slabs and had also been used as chloride threshold indicators in concrete structures [Fuhr and Huston, 1998; 2000].

A sol-gel based fibre optic chloride sensor has been developed by Xie et. al, [2004] and McPolin, [2005]. This chloride sensor was based on impregnating different chloride sensitive indicators, such as silver nitrate, silver chromate and another fluoresceine based indicator. Similar to the sol-gel based pH sensor, the sol-gel with chloride indicator was attached to the tip of 600µm silica fibre using an epoxy adhesive and then covered with protective sheathing, as shown in Fig. 29. The calibration graph obtained at chloride concentrations of 1%, 2% and 3% with silver nitrate indicator is shown in Fig. 30. This investigation has shown the scope for potential use of sol-gel material as an interactive membrane containing chloride sensitive indicator, which could be used for monitoring chloride content in concrete structures. Further research in this area is needed to explore chloride sensitive indicators which are reversible in nature.

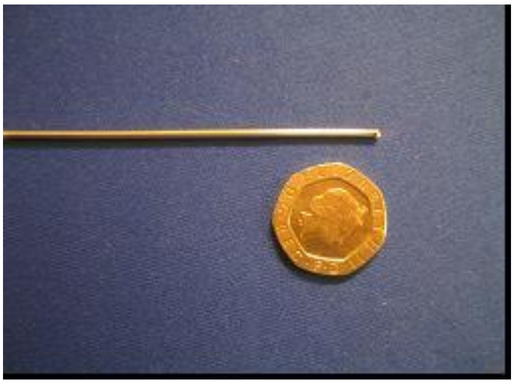

Fig. 29. Sol-gel based chloride sensitive fibre optic probe [Xie et. al, 2004; McPolin, 2005]

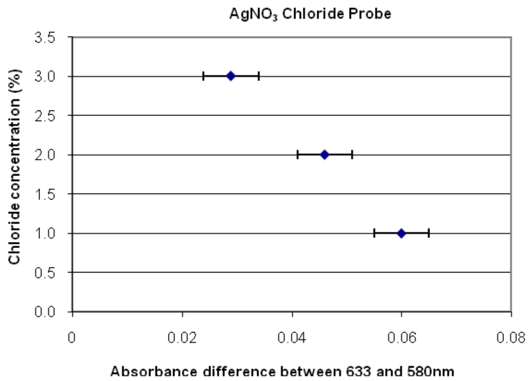

Fig. 30. Calibration of sol-gel based chloride probe using silver nitrate as indicator [Xie et. al, 2004; McPolin, 2005]

In a recent research another chloride sensor was developed based on fluorescence quenching using Lucingenin indicator dye encapsulated in sol-gel [Laferriere et. al, 2008]. This sensor showed a linear correlation between intensity ratio and chloride concentration. In this study the sensors were embedded in mortar samples at different depths and the free chloride concentrations were monitored whilst the mortar blocks were subjected to marine environmental conditions.

5 Conclusions

In this paper, numerous sensors based on electrical and optical fibre technology have been presented and results reported. The work is on-going at many centres world-wide and continues to provide considerable promise for new monitoring systems with major implications for buildings and civil infrastructure for the future. It has been demonstrated that both the fibre optic sensor probes and the covercrete electrode array could be used to monitor various physical and chemical characteristics of concrete that are directly related to its durability. There are certain advantages and disadvantages with each of these techniques, but a combination of these methods would ensure that a proper maintenance strategy could be developed and huge sums currently spent on repair and rehabilitation works saved. This would leave to more money available for capital development work in the future.

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