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Novel Fibre Optic Sensors for Monitoring Physical and Chemical Changes in Concrete Structures

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ABSTRACT: Reinforced concrete structures are no longer considered to be maintenance free due to the frequent occurrence of their premature deterioration. Both the structural and environmental loadings affect the performance of structures in service. Therefore, it is important to monitor the response of structures on a continuous basis from their inception so that deviations from the expected behaviour can easily be identified and appropriate intervention strategies introduced to ensure that the structures do not fail prematurely. Such a strategy could reduce the overall life cycle costs of structures by allowing a more rational approach for scheduling the inspection and maintenance programmes and to the assessment of repair options. Optical fibre sensor systems have emerged during the past ten years to assist in structural health monitoring applications. The authors have been developing fibre optic sensors for monitoring the durability of concrete structures. These are summarised in this paper and the potential of these sensors to assist in predicting the service life of structures is highlighted.

1. INTRODUCTION

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, such as those experienced in marine environments, they tend to deteriorate rather in an alarming rate. The most commonly reported deterioration mechanisms affecting concrete durability are: (a) corrosion of reinforcement as a result of carbonation, chloride ingress and leaching (account for more than 50% of the reported cases), (b) freeze-thaw deterioration, (c) crystallisation of salts in pores, (d) sulphate attack, (e) acid attack, (f) alkali attack, (g) alkali-silica reaction, (h) cracking in both the pre-hardening and hardened states, (i) fire damage and (j) abrasion (BCA, 1997). The movement of aggressive gases and/or liquids from the surrounding environment into the near surface zone of the concrete (Figure 1), followed by physical and/or chemical changes in their internal structure is primarily responsible for the premature deterioration of reinforced concrete structures by one or a combination of the above mechanisms (Basheer and Nolan, 2001). 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 and sea water, 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.

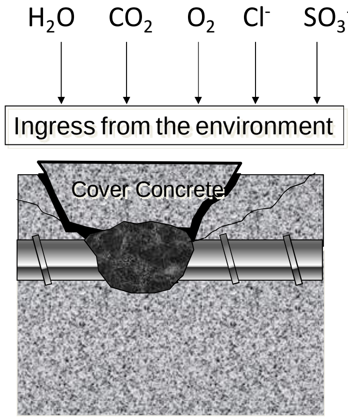

Figure 1. Environmental penetrations into concrete

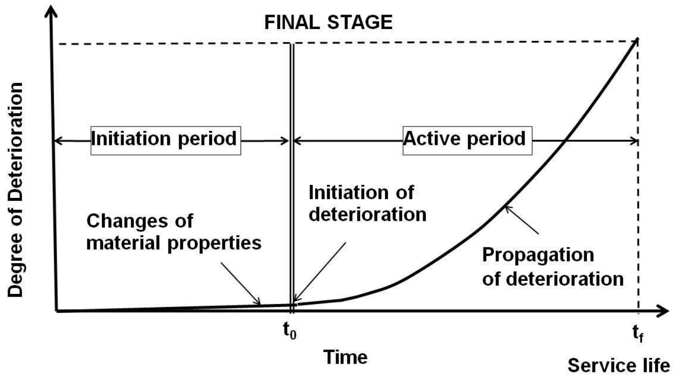

Figure 2. Usefulness of continuous monitoring of structures

Figure 2 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 change, second and crucial stage where initiation of deterioration happens and third stage where propagation of deterioration takes place.

The conventional approach for the diagnosis of deterioration process involves performing chemical analyses using cores cut from the structure. 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. Figures 1 and 2 suggest that most structures are likely to encounter one or more forms of deterioration, unless preventive maintenance are carried out on an ongoing basis to increase the time before the initiation of deterioration. During the initiation phase (Figure 2), information on the ingress of deleterious substances into the structure and/or their effects on the microstructure of concrete can be used to determine t_0. The data thus obtained are invaluable for scheduling when to carry out cost-effective repair and rehabilitation works.

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 Schieβl'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 (Schieβl and Raupach, 1992). The sensor system developed by 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) 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).

For the effective monitoring of the durability of concrete structures, an integrated system containing combination of sensors is needed, which can provide temporal and seasonal variations in quality of concrete cover and reinforcement. The integrated system of sensors should include a combination of sensors that are capable of monitoring physical and chemical changes which take place in concrete structures. The fibre optic sensor technology is ideally suited for integrating different sensing techniques and provide real time information on the physical and chemical changes of a host structure. The data obtained from the integrated sensor system can be used in mathematical models for predicting its service life.This paper presents the development of novel sensors based on fibre optic techniques for monitoring physical and chemical parameters, such as temperature, strain, moisture, pH and chloride, which are crucial to predict the durability of concrete structures.

2. DEVELOPMENT OF FIBRE OPTIC SENSORS FOR ASSESSING THE DURABILITY OF CONCRETE STRUCTURES

2.1 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 Figure 3. Figure 4 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 $\mu\varepsilon$ for ERSG and 64 $\mu\varepsilon$ 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.

2.2 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 Figures 5. The moisture ingress in concrete sample was monitored by measuring the changes in Bragg wavelength, as shown in Figure 6.

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 Figure 7. 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 30mm^3 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 Figure 8. 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.

2.3 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).

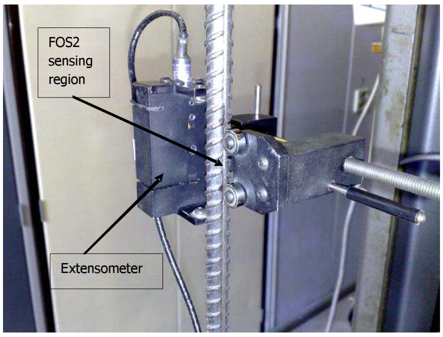

Figure 3. Steel bar with FBG sensor attached along with extensometer

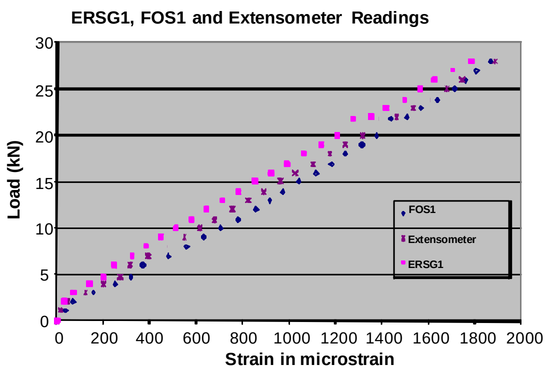

Figure 4. Comparison of results from FOS1(FBG), ERSG1 and extensometer showing change in strain (µε) as a function of load (kN)

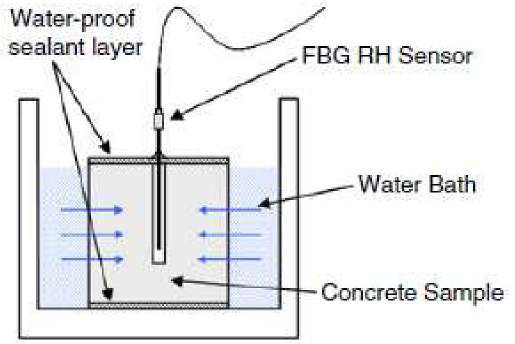

Figure 5. The fibre optic RH probe inserted centrally to monitor ingress of water

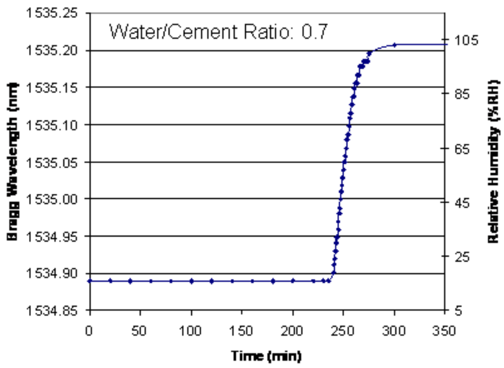

Figure 6. The change in Bragg wavelength due to ingress of water in concrete sample

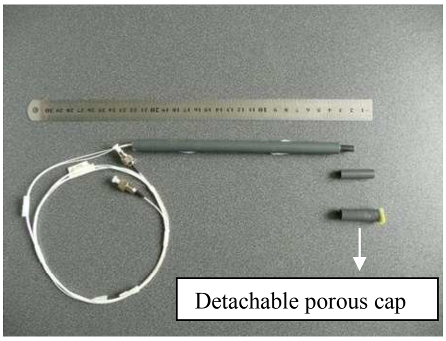

Figure 7. FOS-RH probe with FBG based humidity and temperature sensors

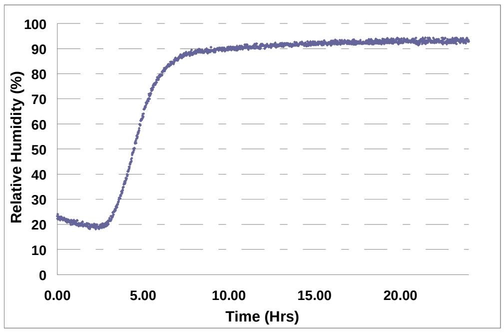

Figure 8. Change in RH with time monitored in concrete in a capillary rise test using Fibre optic RH probe

The authors 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 Figure 9. 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.

2.4 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. Inaddition, other chemical sensors based on fluoroscent technique such as chloride sensors are pH dependant and therefore has a need to monitor pH for applying corrections on chloride concentration measurements. These pH sensing 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). 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 Figure 10. 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 Figure 11. 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).

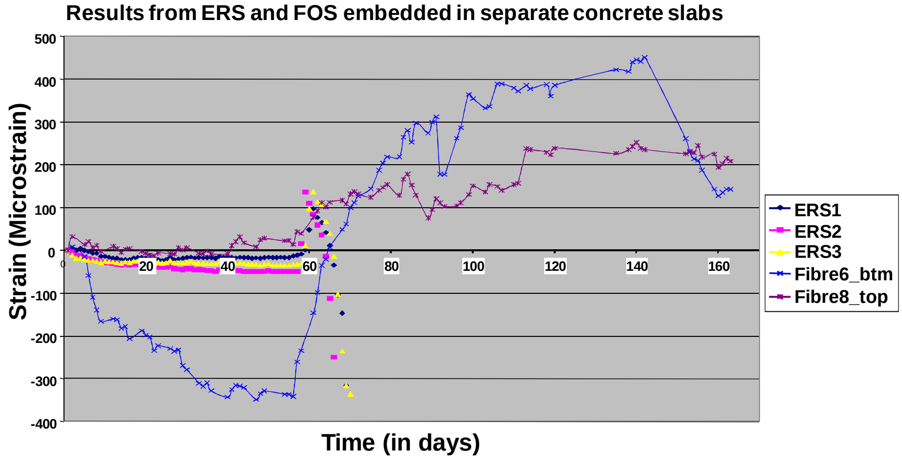

Figure 9. Strain measurements from ERSGs and FBG sensors during accelerated corrosion test

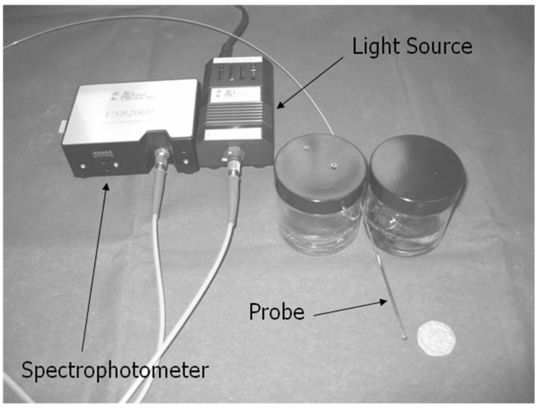

Figure 10. Fibre optic pH sensor set-up

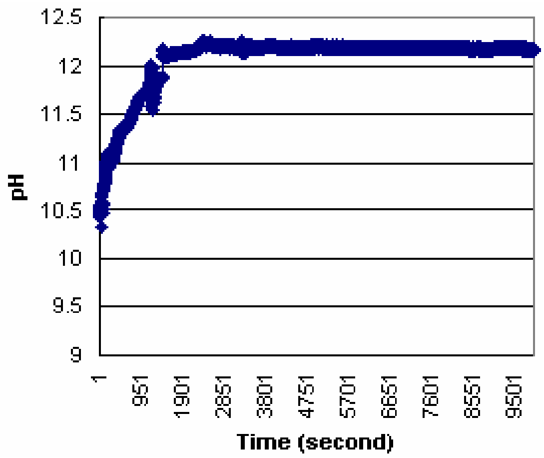

Figure 11. pH change with time in mortar sample using sol-gel based pH probe

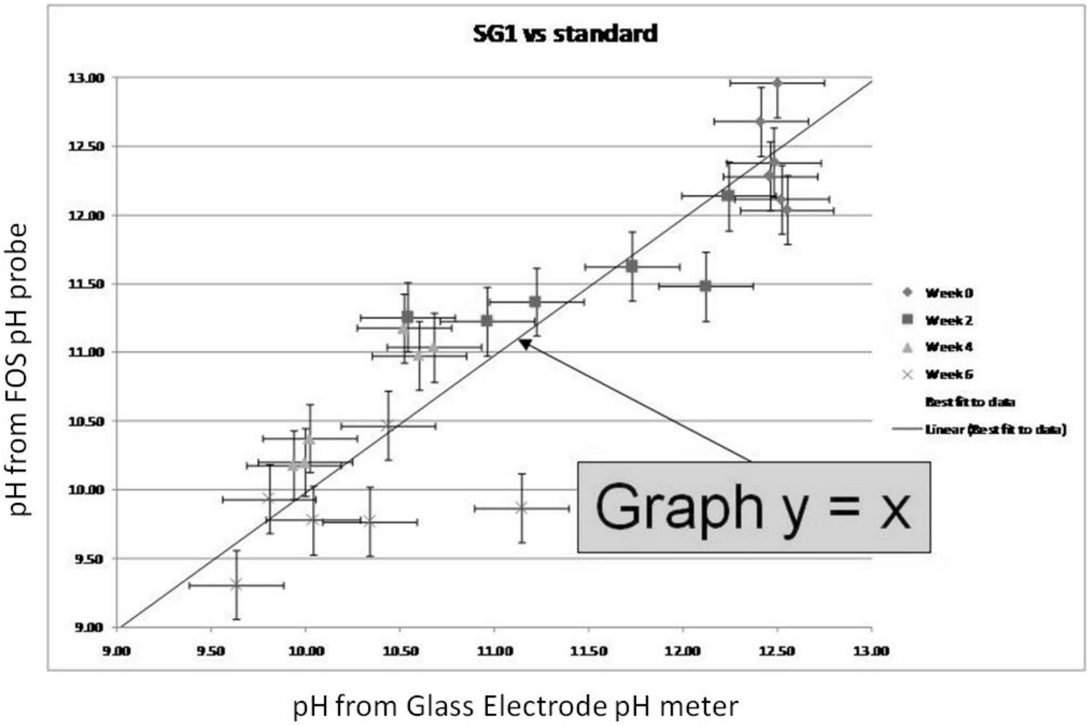

Figure 12. Comparison of fibre optic pH sensor with standard glass pH electrode for determining the effect of different degrees of carbonation on the pH of concrete.

Figure 12 shows the influence of carbonation of concrete on pH when concrete samples were subjected to different durations of carbonation. The pH was measured using both the fibre optic pH sensor and traditional glass pH electrode. This figures illustrates that the influence of carbonation of concrete can be determined reliably using the sol-gel based pH sensor. In this case, both the glass electrode pH sensor and the Fibre Optic pH sensor gave similar values of pH at various degrees of carbonation.

2.5 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 and Wang, 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 ($AgNO_3$), 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.

A sol-gel based fibre optic chloride sensor was developed by the authors in their early work (Xie *et. al*, 2004). 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 Figure 13. The calibration graph obtained at chloride concentrations of 1%, 2% and 3% with silver nitrate indicator is shown in Figure 14. 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 is needed to explore chloride sensitive indicators which are reversible in nature.

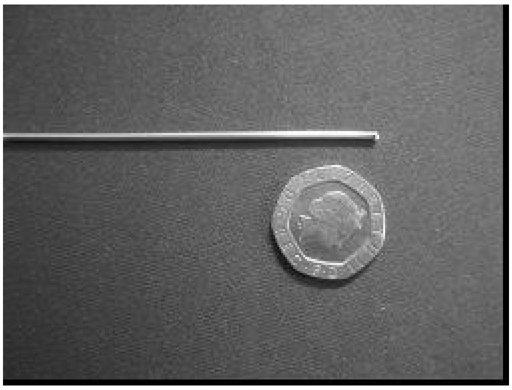

Figure 13. Sol-gel based chloride sensitive fibre optic probe

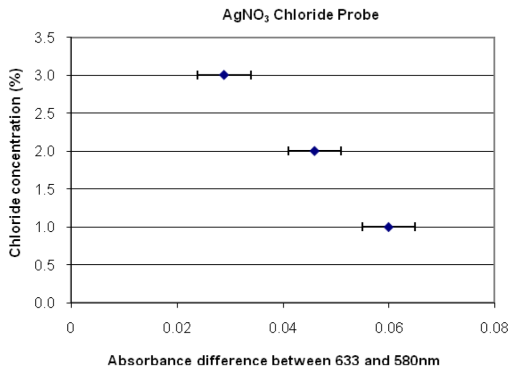

Figure 14. Calibration of sol-gel based chloride probe using silver nitrate as indicator

3. CONCLUSIONS

In this paper, numerous sensors based on optical fibre technology have been presented and results reported. It has been demonstrated that the fibre optic sensor probes could be used to monitor various physical and chemical characteristics of concrete that are directly related to its durability. Although they are very sensitive to variations in physical and chemical characteristics of concrete, their longer term performance in concrete is not yet known. These sensors should perform at least for 10 years in concrete structures for them to be used for predicting the service life of concrete structures in various exposure environments. Further research is needed in all aspects of their application before they are routinely embedded in concrete structures.

4. REFERENCES

Arregui, F.J., Yanjing, L., Matias, I.R. and Claus, R.O., 1999, Optical fiber humidity sensor using a nano Fabry-Perot cavity formed by the ionic self assembly method, Sensors and Actuators, B 59, 54-59.

Basheer, P.A.M. and Nolan, E., 2001, Near surface moisture gradients and in-situ permeation tests, Construction and Building Materials, 15, 105-114.

Basheer, P.A.M., Grattan, K.T.V., Sun, T., Long, A.E., McPolin, D. and Xie, W., 2004, Fiber optic chemical sensor systems for monitoring pH changes in concrete, Advanced Environmental, Chemical and Biological Sensing Technologies II, Edited by Vo-Dinh, t, Gauglitz, G and Lieberman, R.A, Proceedings of the SPIE, Vol. 5586, 144-153.

British Cement Association (1997), Development of an holistic approach to ensure the durability of new concrete construction, BCA Research Report, C/21.

Cosentino, P., Grossman, B., Shieh, C., Doi, S., Xi, H. and Erbland, P., 1995, Fiber-Optic chloride sensor development, Journal of Geotechnical Engineering, Vol-121, No. 8, August, 610-617.

Dong, S., Luo, M., Peng, G. and Cheng, W., 2007, Broad range pH sensor based on sol–gel entrapped indicators on fibre optic, Sensors and Actuators B: Chemical, Vol. 129, Issue 1, 94-98.

Fuhr, P.L., Huston, D.R., McPadden, A.J. and Couley, R.F, 1996, Embedded chloride detectors for roadways and bridges, SPIE, Vol: 2719, 229-237.

Fuhr, P.L. and Huston, D.R., 1998, Corrosion detection in reinforced concrete roadways and bridges via embedded fibre optic sensors, Smart Mat. Struct. 7, 217-228.

Giaccari, P., Limberger, H.G. and Kronenberg, P., 2001, Influence of humidity and temperature on polyimide-coated fiber Bragg gratings, OSA Trends in Optics Photonics Series: Bragg Gratings, Photosensitivity, Poling in Glass Waveguides, Vol. 61, Washington, DC, USA.

Healy, W.M., 2003, Moisture sensor technology-A summary of techniques for measuring moisture levels in building envelopes, ASHRAE transactions, V.109, Pt.1.

Korostynska, O., Arshak, K., Gill, E. and Arshak, A., 2007, Review on state of the art in polymer based pH sensors, Sensors, 7, 3027-3042.

Laferriere, F., Inaudi, D., Kronenberg, P. and Smith, I.F.C., 2008, A new system for early chloride detection in concrete, Smart Materials and Structures, vol. 17, num. 4, 4501-4508.

Laytor, M., Calvert, S., Taylor, T., Schulz, W., Lumsden, R. and Udd, E., 2002, Fiber optic grating moisture and humidity sensors, SPIE proceedings, vol. 4694, 210- 218.

Leung, C.K.Y., Wan, K.T. and Chen, L., 2008, A novel optical fibre sensor for steel corrosion in concrete structures, Sensors, 8, 1960-1976.

McCarter, W.J. and Ezirim, H., Emerson, M., 1992, Absorption of water and chloride into concrete, Magazine of Concrete Research, 44, No. 158, March, 31-37.

McCarter, W.J., Emerson, M. and Ezirim, H., 1995, Properties of concrete in the cover zone: developments in monitoring techniques, Magazine of Concrete Research, 47, No. 172, Sept., 243-251.

McPolin, D., 2005, Profiling of carbonation and chloride distributions in concretes and development of novel fibre optic sensors, PhD Thesis, Queen’s University Belfast, Northern Ireland, UK, November 2005, 217-225.

Pascal, K., 2002, Construction material monitoring with optical hair hygrometers, PhD thesis, École Polytechnique Fédérale De Lausanne, SwitzerLand.

Schieβl, P. and Raupach, M., 1992, Monitoring system for the corrosion risk for steel in concrete, Concr. Int. 14(7), 52-55.

Singh, N., Jain, S.C., Aggarwal, A.K., Singla, M.L. and Singh, M., 2000, A simple fibre optic technique for in-situ corrosion sensing in structures, Non-destructive evaluation of aging materials and composites IV, Editors: Baaklini, G.Y., Lebowitz, C.A. and Boltz, E.S., Proceedings of SPIE, Vol. 3993, 201-205.

Staneva, D. and Betcheva, R., 2007, Synthesis and functional properties of new optical pH sensors based on benzo[de]anthracen-7-one immobilised on the viscose, Dyes and Pigments, Vol. 74, Issue 1, 148-153.

Tang, J.L., Wang, J.N., 2007, Measurement of chloride ion concentration with long period grating technology, Smart Materials and Structures, Vol-16, 665-672.

Xie, W., Sun, T., Grattan, K.T.V., McPolin, D., Basheer, P.A.M. and Long, A.E., 2004, Fibre optic chemical sensor systems for internal concrete condition monitoring, Second European workshop on optical fibre sensors, Edited by Lopez-Higuera, Jose, M. and Culshaw, B., Proceedings of the SPIE, Vol. 5502, 334-337.

Yeo, T.L., Sun, T., Grattan K.T.V., Parry, D., Lade, R. and Powell, B.D., 2005a, Polymer-coated fiber Bragg grating for relative humidity sensing, IEEE Sensors Journal, Vol-5, No-5, 1082-1089.

Yeo, T.L., Sun, T., Grattan K.T.V., Parry, D., Lade, R. and Powell, B.D., 2005b, Characterisation of a polymer-coated fibre Bragg grating sensor for relative humidity sensing, Sensors & Actuators B, 110 148.