Sensors and Materials, Vol. 16, No. 3 (2004) 133–158
MYU Tokyo

S & M 0553

Role of Sensors in Corrosion Monitoring and Durability Assessment in Concrete Structures: the State of the Art

Tae-Hyun Ha*, Srinivasan Muralidharan[1], Jeong-Hyo Bae, Yoon-Cheol Ha, Hyun-Goo Lee, Kyung-Wha Park and Dae-Kyeong Kim

Underground Systems Group, Korea Electrotechnology Research Institute, 28-1, Seongju-dong, Changwon, 641-120, Korea
[1]Invited Scientist from Concrete Structures and Failure Analysis Group, Corrosion Science and Engineering Division, Central Electrochemical Research Institute, Karaikudi - 630 006, Tamilnadu, India

(Received March 18, 2004; accepted May 28, 2004)

Key words: sensors, corrosion monitoring, concrete structures, sensing devices, sensing operations

Many extensive studies in the area of sensor technology for corrosion monitoring in concrete structures have increasingly been carried out in recent years. In this paper, the principles and use of various sensors involved in the health monitoring of concrete structures are described. Special attention was given to the review of various sensing devices, the selection of reliable sensing devices for detecting reinforcement corrosion in particular environments and the efficiency of the devices used. Various sensing operations in new and existing concrete structures for corrosion risk, humidity, temperature, strain and stress are also described.

1. Introduction

Corrosion of steel in reinforced concrete structures is a major problem in North America, Europe, the Middle East and other parts of the world. Chloride-induced rebar corrosion damage results mainly from the use of deicing salts in cold climates and/or from exposure to marine environments. Carbonation damage is a further important type of degradation. Mehta and Burrows reported that, to build environmentally sustainable concrete structures, 21st century concrete use must be driven by considerations of durability instead of strength.(1) Many reinforced concrete structures have shown excellent service

*Corresponding author, e-mail address: thha@keri.re.kr

with minimal maintenance. However, as the infrastructure ages, it has become apparent that some environments are more severe than was originally thought, and some construction and design problems have led to lower service life and higher maintenance costs than originally envisaged. The worst of these problems is caused by corrosion of steel in concrete, either due to pH reduction (carbonation) or localized corrosion (chloride attack). One of the latest estimates from the USA is that the cost of damage to bridges and car parks due to deicing salts alone is between $325 and $1000 million per year. In the UK, the department of transport estimates a total repair cost of £616.5 million due to corrosion damage to motorway bridges. These bridges represent about 10% of the total bridge inventory in the UK.(2,3) There are similar statistics for Europe and particularly the Middle East. Deterioration occurs on buildings and other structures as well as bridges.

The need for permanently embedded corrosion monitoring devices to monitor the development of corrosion problems on a new or existing reinforced concrete structures before embarking on repair or rehabilitation of the structure has been studied. There are many devices for investigating corrosion problems, because no single technique exists which tells an engineer what he needs to know, namely how much damage there is on a structure now and how rapidly the damage will grow with time. Broomfield *et al.* reported that "snapshot" surveys can give a more complete picture of the changing condition of a structure over time as well as in the three physical dimensions of the structure.(4)

2. What are Corrosion Probes or Sensors?

One approach to corrosion monitoring is the use of the component/structure itself for corrosion measurements. However, when this is not practical, separate corrosion probes (sensors) can be installed to monitor corrosion. The use of sensors usually facilitates the measurement of corrosion damage in a well-controlled manner over a relatively small sensor area.(5) The advantages of using corrosion probes for monitoring include:

1. Corrosion measurements can be performed in a controlled manner, without affecting the actual component/structure.
2. Probes usually represent small "samples" that can be periodically removed from the main component/structure and examined in detail.
3. The ability to remove a sample can facilitate the correlation of the sensor signal with the nature of the corrosion on the sensor.
4. Probes can be used to evaluate "what if" scenarios. What if we change the material, surface finish, heat treatment, stress level, interrupt the cathodic protection (CP) system, and so forth.
5. Highly sensitive corrosion measurements can be performed on sensors to provide early warning of potential problems. Such techniques may not be fundamentally applicable to the actual component/structure.

3. Need for Sensors

Corrosion sensing systems have been classified into intrusive (invasive) or non-intrusive (noninvasive) categories. In the former, corrosion sensors "intrude" into a structure to access the corrosive environment directly. When considering so-called smart structures, the distinction between corrosion sensors and the structure itself tends to become blurred. Should a smart coating that indicates corrosion damage be described as a corrosion sensor or as an integral part of the structure? In the use of sensors for direct corrosion measurements, it is important that the sensors actually be representative of the structure or the component being monitored. Seasoned professionals have often remarked that this is often a case of "the devil is in the details." In the words of one professional: "When you say the corrosion sensor is flush, make sure it is flush." For example, localized fluid turbulence created by a protruding sensor can potentially have a major impact on the damage mechanism(s) and the rate of damage. For successful corrosion monitoring programs, attention to sensor details is most essential; many failures can be traced to shortcomings in this area. If the corrosion sensor is fundamentally flawed, investments in sophisticated monitoring hardware, computing systems, data transfer and software may be largely wasted. While sensor design, manufacture and installation can clearly be complex, formal guidelines or standards are, unfortunately, rarely available. Therefore, at times, sensor designs and positioning strategies simulating worst case conditions may be deemed prudent.

4. Survey of the Condition of Concrete Structures

A survey of conditions is often required to understand the phenomenon and to take necessary remedial measures. Frequent surveys are required despite the limited accessibility and complexity of the concrete structures. Measurements should be made based on sound principles, and interpretations of the data should be based on logical scientific reasoning. The following are a few of the essential steps to monitor deteriorated structures:

Corrosivity of the environment: The corrosivity of the environment is tudied by analyzing the pollution level of chloride and sulphate in the atmosphere. A salinity value of more than 100 $mg/m^2/day$ for chloride and even a trace amount of sulphate are reported to be favourable values to reinforce corrosion.[6] The pH, hardness, chloride and sulphate levels in water must also be analysed.

Electrical resistance technique: The time at which the corrosion of steel commences and the rate at which it proceeds depend upon properties of the cement paste and the permeability of the concrete. Because the electrical conductivity of concrete is an electrolytic process which takes place by ionic movement in the aqueous solution within pores of the cement matrix, it follows that a highly permeable concrete has a high conductivity and low electrical resistance. Thus, knowledge of the electrical resistance of concrete provides a measure of the possible rates of corrosion of steel embedded in it.

Concrete cover: The actual cover of concrete provided for embedded steel reinforcements is assessed using an instrument called a profometer, which works on the principle of eddy currents.

Visual examination: The various vulnerable parts of structures are examined visually. This is a basic step in corrosion monitoring of concrete structures.

Loss of alkalinity and chloride contamination: The loss of alkalinity and chloride contamination indicate the nature of corrosion of concrete structures.

Half-cell potential survey: The half-cell potential survey gives only the probability of reinforcement corrosion. The measurement of open circuit potential, which is a thermodynamic quantity, does not indicate the extent and rate of corrosion.[7]

Surface potential measurements: Surface potential measurements are made whenever the rebar is not exposed for monitoring. This technique also does not indicate the corrosion rate.

Resistivity meter: A four-probe or two-probe resistivity meter is used for this purpose.

Corrosion cell ratio: This number is calculated from the surface potential and resistivity measurements.

The resistivity of the concrete, linear polarisation and half-cell potential survey are considered permanent corrosion monitoring techniques in both new and existing reinforced concrete structures.[4]

Several instruments have been developed for corrosion rate monitoring on concrete structures. The following instruments have been reported in the literature:[3,8] GECOR (GEOCISA, Madrid, Spain),[9] FHWA (Federal Highway Work Administration, Washington, DC),[10] CAPCIS (Corrosion and Protection Centre Industrial Services, Manchester, UK), 3LP (K.C.Clear, Inc.),[11] Portable Corrosion Monitor (Nippon Steel Corporation)[12] and ULFACIS (Ultra Low Frequency AC Impedance Spectroscopy, Standard Research Institute, Menic Park, CA).

Each technique has its own advantages and disadvantages. No standard, fool-proof technique is available for perfect corrosion monitoring of concrete structures. Corrosion probes or sensors can give a real picture of the systems. The objectives of this paper are to review the different kinds of sensors and modes of sensing operations and their role in corrosion monitoring and assessing the durability of concrete structures.

5. The Importance of Corrosion Monitoring in Concrete Structures

The technique of conducting a survey of reinforced concrete structures suffering from reinforcement corrosion is now well documented, and a number of techniques can be used to carry out such an assessment.[13–20] Muralidharan and coworkers utilized many electrochemical techniques to assess the corrosion of fly-ash-blended cements in chloride-contaminated concrete.[21–26] All of these techniques can be used in isolation or combination to provide an integrated approach to the condition of a structure. However, because concrete engineers are interested in the rate of deterioration of structures, it is useful to monitor changing condition with time. This is now being carried out on new structures with long lifetime requirements and older structures when corrosion damage has been found and repair is being deferred due to cost, logistical or other reasons. Currently available probes do not meet all requirements. A number of new innovative, inexpensive probes for monitoring existing structures are therefore being developed, covering the most important deterioration mechanisms: corrosion of reinforcement, carbonation of concrete, freeze-thaw damage, alkali-aggregate reaction, and mechanical damage (overloading).

The progress of these mechanisms can be predicted by monitoring key material parameters (temperature, moisture, pH, chloride concentration, corrosion current / rate / initiation), either on the surface or as a profile through the concrete in the structure, as well as mechanical parameters (strain, deflection, vibration, acoustics). The final result is an

integrated system for monitoring existing structures that includes:
1) Prototypes of integrated monitoring systems,
2) Manual for site-tailoring of monitoring systems,
3) Prototype of an integrated model for damage development,
4) Prototypes of new innovative, inexpensive probes, and
5) Local data-collecting units combined with a long-distance data-transfer system. It is estimated that the use of this system could generate reductions on the order of 15% of current operating costs. In addition, the design of new construction projects benefits from the improved predictive models, yielding an additional savings on the order of 10% in life cycle costs.

Some of the field monitoring methods are:
1) Condition assessment and vital testing of concrete structures using advanced nondestructive techniques such as radar, high-energy radiography, and seismic methods (Impact Echo, SASW and UPV).
2) Electrochemical methods for evaluation of the corrosion condition of reinforcements including half-cell potentials and galvanostatic pulse measurements.
3) Permanent monitoring of concrete condition and reinforcement corrosion by embedded probes and reference electrodes.
4) Evaluation of potential durability of concrete structures and preparation of suitable strategies for maintenance and repair.
5) Laboratory analyses of concrete such as petrographic analysis, measurement of carbonation, determination of chloride distribution and chloride threshold values for initiation of corrosion.
6) Design of CP for reinforcement in concrete structures and quality assurance of installation.

Many different sectors of the industry, including bridge authorities, nuclear power, offshore, housing, construction, harbour structures are utilizing sensors for corrosion monitoring.

6. Sensors for Corrosion Monitoring in Concrete Structures

6.1 *Corrosion risk sensors*

6.1.1 *Chemical microsensors*

Compared to normal-sized sensors, chemical microsensors are exposed to a higher corrosion risk.(27) Corrosive damage can be caused by both the direct attack of the medium being measured on the chemically sensitive layer and the corrosion of the substrate materials or the electrical contacts due to absorption or penetration of moisture through the encapsulating material. Corrosion phenomena on chemical sensors have been investigated using electrochemical methods such as the measurement of electrode potentials and sensor output signals or the measurement of electrochemical noise, by resistance and impedance measurements, by gravimetric methods, and by microscopic examinations of the specimen under test. pH glass electrodes, pH sensors, semiconductor-based miniaturized oxygen sensors and zirconia-based potentiometric gas sensors belong to this category.(28) The lifetime and performance of sensors are strongly influenced by the operating temperature of the sensor and the chemical environment to be analysed. Mainly conductometric and potentiometric measurements,[29] polarisation methods, impedance spectroscopy, investigations of the electrochemical noise and microscopical methods (optical and SEM) are utilized for studying the corrosion behavior of construction materials.

6.1.2 *Ring sensors or macrocell sensors*

Since 1990, a special macrocell system, the so-called anode-ladder system, has been used worldwide to monitor new concrete structures in addition to other systems. Figure 1 shows the anode-ladder system used to monitor the corrosion risk of the reinforcement in concrete structures.

This sensor system indicates the depth of the critical chloride content that initiates corrosion, i.e., the critical depth of the reinforcement with respect to corrosion. Subsequently, the time-to-corrosion can be determined, enabling owners of buildings to initiate preventive protection measures before cracks and spalling occur. By measurement of the potentials and the electrical resistance of the concrete around the sensors, an estimation of the humidity, the availability of oxygen and the corrosion behavior after depassivation is possible.

The equipment of the anode-ladder system consists of anode ladder element with 6 single anodes including temperature sensors as main monitoring sensors, a cathode bar of 40-cm-long platinum-coated titanium (8 mm dia.) as counter electrode for the electrical measurements against the anode ladder, and reinforcements. The terminal box has a geometry as small as possible to ensure that it can be moved through the reinforcement from the sensor location to the final measuring position in most cases. The step-by-step

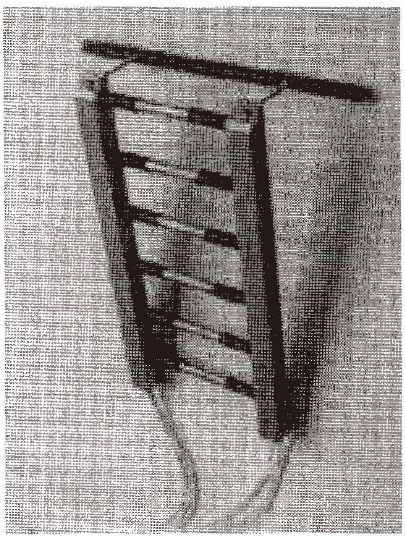

Fig.1. Anode-ladder system.

installation procedure for the expansion-ring anode into the concrete in the aggressive environment is depicted in Fig. 2.

The development of corrosion monitoring sensors was based on an extensive research program on the main factors influencing chloride-induced macrocell corrosion of steel in concrete. More than 500 concrete specimens with different concrete compositions have been investigated by Raupach and Schiebl under varying environmental conditions.[30] These investigations have been carried out using macrocell current measurements between anodically and cathodically acting steel surface areas. The tests have shown that this technique can also be used to monitor the ingress of aggressive ions such as chloride or carbonation by measuring electrical signals between different steel bars installed at defined locations. In chloride-free and noncarbonated concrete, both anode and cathode are protected against corrosion due to the alkalinity of the solution in the pores of the concrete (passive state). The electrical current between both electrodes is negligibly low under such conditions. If, however, a critical chloride content is reached, or if the pH of the concrete decreases due to carbonation, the steel surface of the anode is no longer protected against corrosion. Provided that the selected cathode material is corrosion-resistant in chloride-contaminated or carbonated concrete and sufficient moisture and oxygen are available, oxygen reduction takes place at the surface of the cathode bar. The local separation of anodically and cathodically acting areas leads to an electron flow between the black steel and the noble metal, which can easily be measured using an external cable connection.

The measuring electrodes are made of steel with a composition similar to that of reinforcing steel to ensure that they will start to corrode at the same time a rebar at the same depth would start to corrode. Comparative tests have been carried out at the Institute for

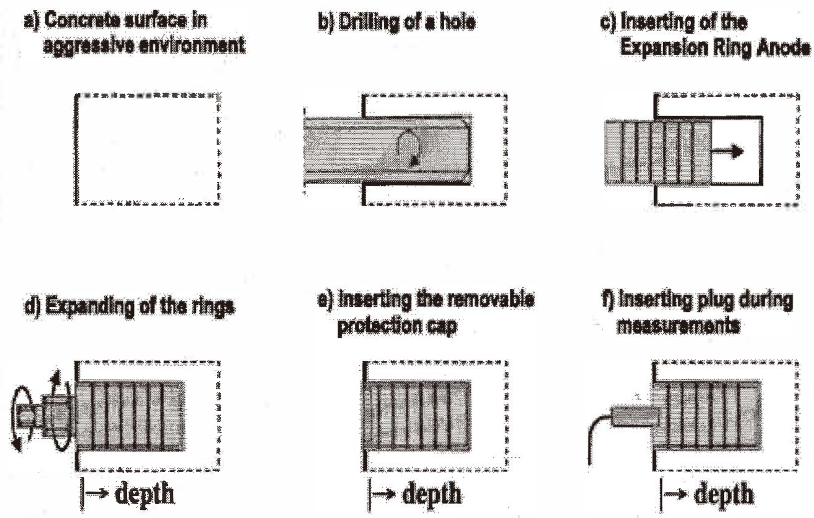

Fig. 2. Expansion-ring anode –> installation procedure.

Building Materials Research of the RWTH Aachen, showing that there was no significant difference in the corrosion behavior of the steel used for the measuring electrodes (anodes) and reinforcing steel, when using different degrees of prerusting before installation into the concrete specimens. Because the results of extensive laboratory and field investigations of the anode-ladder system limit the following alarm values(31) for the el. currents: (1) El current 5 s after coupling < 15 μA (and long-term-current *e.g.* after 24 h < 1,5 μA) indicate no corrosion and (2) El current 5 s after coupling > 15 μA (and long-term-current *e.g.* after 24 h >> 1,5 μA) indicate depassivation. These limit values are related to conventional concretes for nonsubmerged outdoor exposure; this may be slightly different for unconventional concrete compositions or environmental conditions.

This sensor has the following advantages over other sensors:

1) It is not only shown whether the reinforcement corrodes, but it can also be estimated when the reinforcement will start to corrode.
2) The corrosion monitoring system shows the depth of the critical chloride content directly and not the absolute chloride content. Compared to the measurement of chloride profiles, this is a decisive advantage because, as known from experience, the interpretation of absolute chloride content is generally difficult. Therefore, the installation of corrosion monitoring sensors cannot be replaced by taking concrete samples alone for chloride profiles.
3) The use of the corrosion monitoring system is especially economic for inaccessible locations, *e.g.* at the outer surfaces of tunnels or in the tidal zones of pier shafts.
4) When the corrosion monitoring systems are used as an effective integrated part of a maintenance program, the operating costs, i.e., inspection, maintenance and repair costs, can be reduced significantly.

Interesting fields of application are the following:

1) Reinforced concrete structures exposed to aggressive environments (offshore structures, buildings near the coast, bridges, parking structures, tunnels, foundations)
2) Areas with difficult access or without any access (outer areas of tunnels and pipes, foundations and tanks, piers, piles of bridges near the water level)
3) Monitoring the durability of special protection systems for new structures especially with a high designed service life, *e.g.* 100 years (high performance concrete, coatings, inhibitors)
4) Monitoring the durability of special repair systems (cathodic protection, desalination, coatings, inhibitors)

6.2 *Acoustic sensor*

The operation of this sensing system is based on well-known acoustic emission physics. The ability of this sensing system depends on how they detect emissions from corrosion-induced wire failure above ambient noise and to distinguish them from other acoustic events. Furthermore, to be effective, this process should be continuous with minimum interruptions for a significant length of time in order to establish the absence of wire breaks or the rate at which they are occurring. A stressed high-tensile steel elements such as wires, strands, bars are suddenly released the energy at the moment of fracture. This energy is dissipated through the structure in the form of an acoustic response, which can be detected by sensors mounted on the surface of the concrete. The sensor consists of piezoelectric accelerometers connected by cables to the on-site data acquisition terminal with suitable filters.

Cullington *et al.* first demonstrated this sensor in the UK site installation of a monitoring system that detects the fracture of wires in post-tensioning tendons by listening with acoustic sensors attached to the surface of the concrete.(32) Trials have shown the system to work reliably for grouted and ungrouted tendons. Acoustic events from other sources such as road traffic are discarded using software and hardware filters at the unattended site. Data from possible wire-fracture events are sent off-site for final identification and positioning. The system runs continuously on site, on a viaduct, with close to 100% up-time. In open and blind trials on the viaduct, 41 out of 44 wire break or facsimile events were correctly located and identified and a further two were correctly located. The system can assist in the management of bridges where the post-tensioning system is at risk from corrosion.

An invasive investigation should be used to confirm the condition at the wire break locations identified by this sensor. It should then be possible to establish a management strategy for the structure, which may require immediate attention, but may equally be perfectly safe for further service until a significant loss of prestress occurs. In these circumstances a monitoring system could play an important part in the immediate and long-term management of the structure.

The quantitative damage estimation of concrete by acoustic emission is reported. Measurement of acoustic emission activity in the uniaxial compression test of a core sample confirmed that acoustic-emission-generating behavior is closely associated with the presence of microcracks in concrete.(33)

6.3 *Chloride ion sensors*

Chloride ions used in deicing agents applied to reinforced concrete corrode the embedded steel and thereby threaten concrete-based civil infrastructure, such as bridges, roads, and parking structures. In fact, the intrusion of chloride ions is the major cause of deterioration of these structures. Corrosion of embedded steel reinforcement in concrete occurs after the level of chloride ions in the concrete in the vicinity of the embedded reinforcement reaches 0.2%. Depending on the exposure environment, the depth of the embedded reinforcement, and the quality of the concrete, corrosion in concrete infrastructure can begin as early as the first few years to as late as 25 years in the life of a structure. This time-to-corrosion parameter for embedded steel reinforcement determines the lifetime of a structure. Numerous studies have been undertaken to study the time-to-corrosion with respect to concrete quality, exposure, and initial chloride levels in the concrete. In these studies, as well as in the everyday maintenance of the infrastructure, the chloride content and concentration profile are measured by crushing concrete samples and evaluating the extracted chlorides through wet chemistry. These methods determine the chloride content by weight based on the concrete sample itself. These tests are typically performed during the later ages of a structure's life when it approaches the end of its predicted lifespan or when evidence of deterioration indicates a potential corrosion problem. Other methods of detecting the initiation of corrosion also have been developed. These methods do not detect or depend on a parameter such as chloride content to determine the corrosion potential, but detect when corrosion is actually occurring. Although the chloride content of the concrete is not the only parameter that determines when corrosion will begin, it is the one parameter that is well established as a major contributor to corrosion.

Thus, a sensor that would report chloride levels from the interior of concrete structures is needed. An embedded nuclear magnetic resonance (NMR) that determines chloride levels in concrete would be an especially attractive solution to the problem because NMR is quite specific in its identification of chloride; also, because there is no chemical interaction of the device with the chloride, it could be easily designed to operate for the predicted lifespan of the structure.

NMR can, in principle, determine the presence and concentration of chloride. NMR is the phenomenon by which a signal is generated when nuclei having nonzero nuclear spin undergo transitions between energy states. A magnetic field, B_0, aligns the magnetic moments of the nuclei, which process around the direction of the applied field. Excitation of these moments with electromagnetic radiation of frequency characteristics of the species of interest causes energy transitions that are detectable. The presence of measurable transitions at known frequencies is a diagnostic of the presence of the species. Chlorine has a nonzero spin, 3/2 in its most abundant isotopes. Thus, chlorine is detectable in principle with NMR. The major components of any remotely deployed NMR sensor are a permanent magnet designed to provide a uniform magnetic field (B_0), a coil that both generates a small excitation magnetic field (B_1) in the sample and receives the signal back from the sample, and electronic components for filtering, mixing, digitizing, and summing the readings taken from the coil. The important and interesting question is whether a compact system incorporating all of these functions can be expected to detect chloride in concrete.

The sample volume is most critical because it governs the number of atoms one can expect to be present. For deployment in concrete infrastructure, the overall system must have a characteristic length scale of less than 5 cm on a side, which is close to the maximum size of coarse aggregate in concrete. A magnetic field of 7–19 T typically is used to obtain a signal; a potential in situ NMR sensor, however, would be limited by available permanent magnet materials to 1 T or less. The magnet occupies much of the volume of the device because it must deliver both a maximum field strength and good uniformity. The solenoid coil connected to the electronic chip might have a diameter of 2–4 mm and would be placed in the barrel of the specially designed permanent magnet. Fundamental calculations of the field homogeneity inside such a package probably constrain the sample size to 1 mm^3. Thus, the research question becomes whether one can reasonably expect to detect chloride in a volume of characteristic dimension (1 mm) with a magnetic field strength less than 1 T.

Although NMR has been used in cement and concrete research since the early 1980's, chloride (^{35}Cl and ^{37}Cl) has been rarely studied due to its low sensitivity. Most chloride-related studies have been carried out with ^{27}Al NMR because aluminum is 100% abundant and has a higher sensitivity than chlorine, and the amount of free chloride ions in Portland cement concrete is inversely proportional to the amount of C_3A and C_4AF. Kirkpatrick *et al.*(34,35) and Yu and Kirkpatrick(36) reported on ^{35}Cl NMR studies for cement research. Their studies were based on suspensions, however, and not on cured cement. Cano *et al.*(37) investigated the penetration of chloride into mortar with two water-to-cement ratios. They used a high concentration of chloride to aid detection. The relatively open structures admitted the chloride over a period of hours, much faster than explained by diffusion; they concluded that advection along pores was the mechanism of penetration.

Laboratory experiments to detect chloride in a cement matrix using pulse nuclear magnetic resonance (NMR) have been conducted[38] to determine whether the sensing of chloride ions by NMR in concrete at low concentrations is really feasible. The studies were confined to only 2% of added chloride by weight of cement or less. NMR sensor is tested on three environments, i.e., chloride in aqueous solution, in laboratory-prepared cement samples, and in a sample of concrete that had aged for two decades in the field.

Chlorine signals were detected with a 2.35-T NMR spectrometer from the cured white Portland cement mixed with sodium chloride. Residual free chloride was detectable in the cement using NMR. By using the measured chlorine signal from a sample taken from a field sample, a parametric study was performed with various values for the magnetic field strength, coil diameter, and measurement time to estimate the signal-to-noise (SNR) ratio of a proposed in situ NMR sensor that would use a 0.5 T magnetic field and a 2 to 4 mm diameter microcoil. According to this parametric study, the SNR of the envisioned in situ NMR sensor averaged for 24 h with a longitudinal magnetic field of 0.5 T and coil diameter of 2–4 mm would be far below 1. However, at magnetic field strengths around 2–3 T and at coil diameters around 50–70 mm, it is estimated that SNR values around 5 can be achieved even for the minimum amount of sampling time considered in this study (3 h). The problem is that homogeneous field strengths of this size would be difficult to produce at remote sites. The challenge would be to somehow concentrate the chloride and average for a long enough time to extract a signal.

The possibility of using Ag/AgCl wire electrodes as in situ sensors of chloride concentration in concrete was studied by embedding them in a series of mortar specimens with different admixed sodium chloride content. They show a sensitive potentiometric response to overall chloride ion concentration. The stability of the potential readings depends on the chloride concentration and allows these electrodes to be used as chloride content sensors in short-term tests.[39] Silver chloride-coated silver wires (Ag/AgCl) are the kind of electrodes that give potentiometric response to variations in the activity of Ag^+ or Cl^- ions in solution and that, in principle, could be embedded in concrete due to their mechanical stability. Recently, Yang *et al.*[40] have reported a localized corrosion sensor consisting of multiple, corrodible, miniature electrodes and tested in different chemical environments. The miniature electrodes were coupled together by connecting each of them to a common joint through independent resistors, with each electrode simulating an area of a corroding metal. In a localized corrosion environment, anodic currents flow into the most corroding electrode and cathodic currents flow out of the less or noncorroding electrodes. These currents are measured from the voltages across the resistors. The variation among the galvanic currents measured from the miniature electrodes responded well to changes in the environment with respect to localized corrosion. It was demonstrated that statistical parameters derived from the currents flowing through the miniature electrodes, such as the standard deviation or the 90^{th} percentile anodic value can be used as indicators for localized corrosion.

6.4 *Automated mapping sensors*

Nondestructive mapping of reinforcement in concrete elements of old buildings may be needed when changes or extensive maintenance is required. It is always needed when reliable design drawings are not available. The mapping indicates the location of reinforcement bars and their diameters and depths of cover. Developing a reliable method for automated mapping of reinforcement bars is needed. The principle here is a selection of a reliable sensing device for detecting reinforcement bars in concrete, and development of algorithmic procedure for manual and automated mapping of the reinforcement. The automatic mapping mode proceeds in two major phases: (1) point determination of a bar; and (2) a straight and bent bar mapping algorithm. The algorithm was tested on a set of rebar configurations by simulation and by full-scale experiments. The automated mapping procedure appears to be robust and reliable, and its mapping tolerance of the location measurement does not exceed 10 mm when compared the manual mapping it is 5 mm. Times required to run automated mapping are half as long as those of manual mapping. The efficiency of the automated mapping is expected to be higher for mapping large surfaces. Automated mapping sensors may be designed on the following techniques:

1) Electromagnetic "covermeters"[41–44]
2) Magnetometer-based sensory systems[45]
3) Microwave scanners[46]
4) Radiographic sensory systems[47]
5) Electrical resistivity measurement systems[48]

The principles involved in the sensing operation are briefly described in the following:

6.4.1 *Electromagnetic "covermeter" sensor system*

All covermeters are electromagnetic in operation. Electric currents in a coil winding in the search head generate a magnetic field which propagates through the concrete and will interact with any buried metal present, such as reinforcing steel. The interaction will be due to either or both of two physical properties of the steel: its magnetic permeability and its electrical conductivity. The interaction causes a secondary magnetic field to propagate back to the head where it is detected by a second coil or in some instruments by modifying the primary field. The signal received will increase with increasing bar size and decrease with increasing bar distance (cover). By making certain assumptions about the bar and specifically by assuming that only one bar is present within the primary magnetic field, the instrument can be calibrated to convert signal strength to distance and hence to indicate the depth of cover.

The covermeter generates an electromagnetic field, and when this field is disturbed by the presence of a bar, an appropriate signal is transmitted to the control unit. The size, location and orientation of the bar can be deduced from the nature of the disturbance. The sensory system consists of three sensing probes - a spot probe for locating rebars, a depth probe, and a diameter probe as shown in Fig. 3.

Covermeter reading measures the range from the cross wire of the probe to the nearest rebar. As shown in Fig. 3, if the rebar diameter "d," the concrete cover "D" and "L" the distance from the intersection point of the probe to the projection line of the rebar axis on

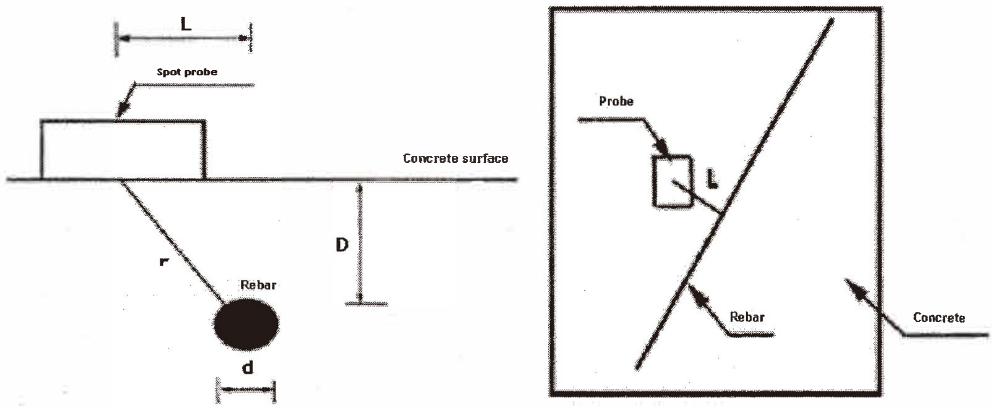

Fig. 3. Position of a covermeter probe on a concrete surface.

the concrete surface, the covermeter reading "*r*" is given by

$$r = \sqrt{[L^2 + (D + d/2)^2]} - d/2. \tag{1}$$

Moving the probe close to the concrete surface along a scanning path in accordance with a predetermined pattern maps the concrete surface. The data from the sensor as well as its location on the scanning grid is transferred to the processing unit of the covermeter. The spot probe then serves to determine the location of the bars, and the diameter probe is used subsequently to determine their size. The principle of operation of the spot probes requires that the orientation of the bar is perpendicular to the scanning path, otherwise the presence of the bar will not be indicated. The accuracy of the covermeter was tested with respect to three concrete specimens of which known and reliable design drawings were available.

British Standard 1881 Part 204: 1988 requires that when measuring cover to a single bar under laboratory conditions, the error in indicated cover should be no more than plus or minus 5% or 2 mm whichever is greater.[42] For site conditions, an average accuracy of plus or minus 5 mm or 15% is suggested as being realistic in the British Standard. Recent developments in covermeters have significantly improved accuracy giving results within better than 1% on average. The British Standard also lists a number of extraneous factors which are potential sources of error, including (1) multiple rebars, laps, transverse steel, or closed-spaced rebars, (2) light wire mesh, buried nails, or other metals between the rebars and the surface, (3) variations in the iron content of the cement and the use of aggregates with magnetic properties, and (4) stray magnetic fields or a surface coating of iron oxide on the concrete. Care should be taken in interpreting the results. Repeated readings are taken to identify the exact location of the rebar.

6.4.2 *Magnetometer-based sensory systems*

These involve a passive technique, which is based on the measurement of the magnetic field of ferrous objects. It can provide data about location, orientation, and depth of reinforcement bars, but bar diameter estimates with this method are not highly reliable. An important factor affecting this method is the significant impact of the magnetic field generated by other ferrous objects situated near the concrete surface. As a result, large measurement errors may occur. An alternative, active application of this method is to use a long solenoid to generate a magnetic field at all points in space. Rebars are magnetized by this field and induce an additional field. The total magnetic field is measured and analyzed to obtain the rebar's exact location.

6.4.3 *Microwave scanners*

This method employs electromagnetic energy emitted in short pulses towards the concrete surface. When a metal obstacle is encountered, an echo is returned, and the location of the obstacle can be deduced from the change in the amplitude of the echo and the time elapsed between the emission of the pulse and the reception of the echo. The diameter of a detected bar cannot be assessed with this method. Four properties associated with microwaves make them practical in nondestructive technique (NDT) of reinforced concrete: (1) their ability to penetrate dielectric materials (*e.g.*, concrete); (2) their reflection from conducting objects (*e.g.*, rebars) and interfaces; (3) the polarizability of the microwave signal; and (4) the relatively small wavelengths used, which makes for small probe sizes. The power output of the transmitted radar signal is very low, thus no special safety precautions are needed. The set-up time of radar for field testing is relatively short compared with other techniques (*e.g.* radiography, electrical resistivity), and data can be gathered quite easily.

6.4.4 *Radiographic sensory systems*

This system uses gamma rays or X-rays directed at the area to be mapped. The bars are identified in their actual shape even at a considerable distance from the concrete surface (500 mm or more). The method requires extensive safety precautions and must be employed by a person specially trained in its use.

Generally, radiography is the most satisfactory technique for finding buried objects. It is suitable for detecting linear and planar objects and for measuring the thickness of the cover. The use of radiography as a nondestructive method for testing concrete is relatively new. Its main applications are determination of the presence of a rebar, its location and size, and evaluation of the condition of concrete such as lack of compaction or the presence of voids, the alignment of strands in the cable duct, voids in concrete, voids in grout, or the snapping of wires.

6.4.5 *Electrical resistivity measurement systems*

This method determines the resistivity of the object and is usually employed to determine the thickness of pavements. It is seldom used in practice to locate rebars embedded in concrete.

The review of methods in this field resulted in the recommendation that, for rebars not very deeply embedded in concrete, the electromagnetic covermeter is the preferred mapping device. It was found to be adequate for both manual and automatic mapping. The covermeter system can detect depth as well as size of bars, and it is simple to operate, both manually and with automatic grippers. The readings, which are recorded digitally, are easy to interpret, and the accuracy of the measurement is within the tolerance usual in building construction. Furthermore, the device is not costly and does not require special safety precautions.

6.5 *SOFO sensors*

Deformation of concrete at a very early age can give rich information about the concrete, particularly the evolution of its mechanical properties. In the literature, so far no reference to tests developed to monitor the evolution of concrete properties from pouring and into a very early age has been found. Deformation at a very early age is indeed not easy to measure because of the viscosity and the low stiffness of the mixture. Classical setups are not appropriate for measurements on nonhardened structures.

Glisic and Simon developed the SOFO (Surveillance d'Ouvrage par Fibers Optiques - Monitoring of Structures by Optical Fibers) system based on low-coherence interferometry in single-mode fibers and allows the measurement of deformations in civil structures built with classical civil engineering materials (concrete, steel and wood).[49] The SOFO sensor consists of two monomode optical fibers, namely, measurement and reference fibers, as shown in Fig.4. The measurement fiber is in mechanical contact with the host structure and follows its deformation, while the reference fiber, placed close to the measurement fiber, is loose and behaves independently from the structure. Any deformation of the structure will result in a change in the length difference between the two fibers.

To monitor the behavior of concrete at a very early age, a stiff SOFO sensor is preferred. By using a standard SOFO sensor, it is possible to measure deformation of concrete at a very early age (thermal swelling and shrinkage). However, by coupling the SOFO with a stiff sensor, it is possible to determine the hardening time of concrete and to measure initial stress in the rebars. It has been successfully tested in different types of structures such as bridges, dams, tunnels and piles and the schematic[49] of this sensor is shown in Fig. 4.

The standard SOFO sensor is composed of two zones: the active zone where the deformations are measured, and the passive zone that serves as an information guide.

6.6 *Strain gages and accelerometers*

Strain sensing is a function required for smart structures. The sensing of irreversible strain allows structural health monitoring. The sensing of reversible strain allows dynamic load monitoring. In general, the sensing of reversible strain is more challenging than that of irreversible strain, since reversible strain can only be monitored in real time whereas irreversible strain does not have to be monitored in real time. Furthermore, reversible strain tends to be smaller than irreversible strain.

The sensing function refers to the ability to provide an electrical response to a strain stimulus. Requirements of strain sensors include the following: wide strain/stress range of

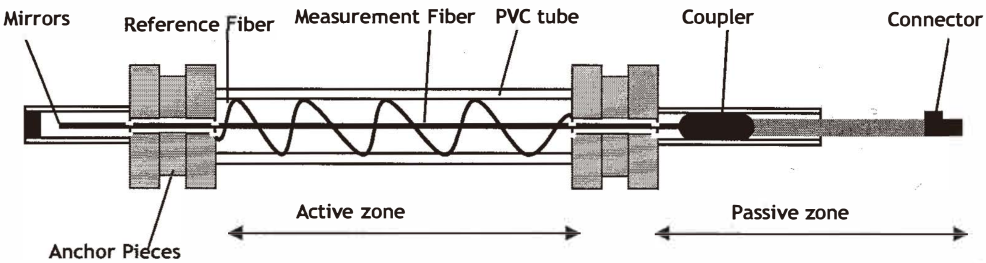

Fig. 4. Standard SOFO sensor.

detection (from small strains up to failure), response being reversible upon stimulus removal (necessary for repeated use of the sensor), ease measuring of response (without the need of expensive peripheral equipment), the sensor having no side effect on the structural properties of the structure, chemical stability and durability, and low cost.

The method uses extensometer sensors, such as the well-known strain gages (SG), and is based on the phenomena of tension state, in which the mortar mass comes near the rebar area after the formation of corrosion products. This technique is based on the principle of tension appearance caused by steel corrosion products. This tension is monitored by embedded strain gage extensometers. Compensation is provided during measurement because of disturbing effects, such as ambient temperature and specimen volume changes. The method is evidently a nondestructive one, directly related to the formation of corrosion products.

The strain gages (30×10×3 mm size) are made of Cu-Ni alloy with acrylic backing and the operating temperature range is from 0 to 150°C. The SG is embedded in reinforcing mortar specimens during casting. Specimens are immersed in a 3.5 wt% NaCl solution and a constant potential is applied between the steel rebar and a graphite electrode to attain conditions of fast rapid corrosion. Batis and Routoulas applied this method in different types of mortar specimens for testing and verification. The reliability of the technique was evaluated by measuring: (1) the gravimetric weight loss of the reinforcing steel bars; (2) the electrical charge flow through specimens; and (3) the porosity of mortar mass. The test results obtained indicate that the method is reliable and suitable for the laboratory study of the corrosion factors and the influence of concrete admixtures in corrosion protection.[(50)]

Cement reinforced with short carbon fiber is capable of sensing its own strain due to the effect of strain on the electrical resistivity. Wen and Chung described this type of piezoresistive strain sensor.[(51)] Addition of carbon fibers to the concrete and making the concrete itself as a strain sensor are new sensing technologies.[(52)] Two coil strain sensors based on stress-annealed $Co_{69}Fe_2Cr_7Si_8B_{14}$ amorphous magnetic ribbons were designed, fabricated and evaluated. The sensitivity is much higher compared with resistance gages allowing low-price electronic portable equipment for outdoor measurements.[(53)] The combination of giant magnetoresistive sensor (GMR) and eddy current sensor is used for high-sensitive stress measurement and basically improves the mechanical stress measurements.[(54)]

The potential advantageous application of accelerometer data for independent verification of the bridge load capacity using a single-degree-of-freedom model has been discussed in the literature.(55) Most often, strain gages are the sensor of choice for this purpose because of their low cost, ease of use, and high reliability. However, recent tests have shown that accelerometers can offer some distinct advantages over strain gages for this purpose. Mostafiz *et al.*(56) studied the accelerometer response and compared the results with traditionally measured strain gage data and concluded that accelerometers are most advantageous when testing reinforced concrete bridges. Because they are almost always cracked to some extent, strain gages must be carefully placed to capture the effects of cracks. Accelerometers capture the global behavior of the beams regardless of the degree of cracking. Additionally, accelerometer data are more useful for measuring vehicle-bridge dynamic interaction, which can lead to better estimates of vehicle impact factors.

6.7 *Optical fiber sensors*

Optical fiber sensors are emerging as a superior nondestructive means for evaluating the condition of concrete structures.(57–63) Optical-fiber-sensor-based instrumentation has been shown to be extremely attractive for the in situ health monitoring, diagnostics and control of civil infrastructure. In contrast to existing nondestructive evaluation techniques, optical fibers are able to detect minute variations in structural conditions through remote measurements. Optical fibers fully integrated into structures will be able to monitor the initiation and progress of various mechanical or environmentally induced degradations in concrete elements. Recent advances in optical fiber sensor technology and the possibility of their use in concrete structures have encouraged the development of a number of research activities. Owing to the inherently interdisciplinary nature of the field of optical fibers, the expertise of researchers active in the study and development of optical fiber sensors covers a wide spectrum of disciplines including concrete engineering, opto-electronics and physics. Ansari published a state-of-the-art on the applications of optical fiber sensors to cementitious composites.(64) The sensors are embedded into a structure to form a novel self-strain monitoring system, i.e., the system can self-detect its health status and send response signals to operators during any marginal situation during service. The embedding sensor, due to its extremely small physical size, can provide the information at a high accuracy and resolution without influencing the dimension and mechanical properties of the structure. Optical fiber sensors present a number of advantages over the conventional strain-measuring devices: providing absolute measurements, enabling the measurement of the strain at different locations in only one single optical fiber using multiplexing technique, having a low manufacturing cost for mass production, and ability to be embedded into a structure without affecting the mechanical properties of the host materials.

Currently, three different types of optical fiber sensor arrangements have been developed in real-life applications; they include localized, multiplexed and distributed sensor systems. The localized optical fiber microbend strain sensor is shown in Fig. 5.

Optical fiber strain sensors have been successfully embedded in glass and carbon fiber reinforced polymer (GFRP and CFRP) reinforcements during pultrusion. The specific application is the use of the smart composite reinforcements for strain monitoring of innovative civil engineering structures. The experiments conducted showed that the strain

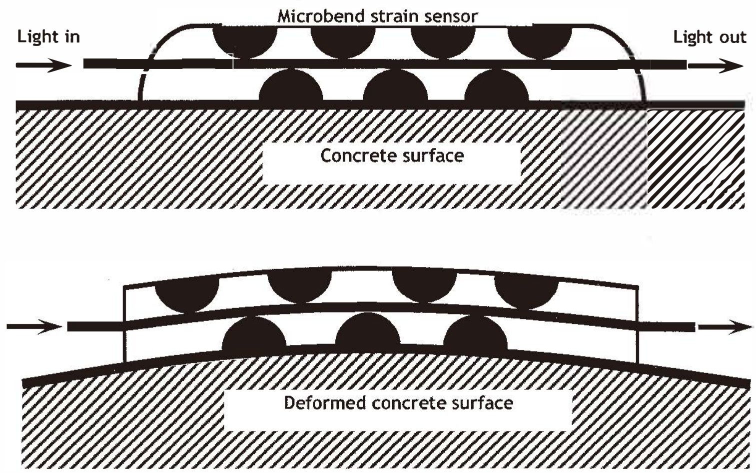

Fig. 5. Localized optical fiber sensor.

from the embedded optical fiber sensors conformed well with the corresponding output from extensometers or foil gages.

The design, fabrication and implementation of long-period-grating (LPG)-based optical fiber sensors for the nondestructive evaluation of smart structure systems has been reported.(65) The LPG sensors, fabricated of or from standard SMF-28 corning fiber, were attached to pieces of rebar and cyclically loaded from no-load through 35 kN loads; sensor performance was monitored using an optical spectrum analyzer. A mechanical extensometer was collocated with the LPG sensor for comparison. Short-period optical fiber Bragg grating (FBG) sensors were also tested under similar conditions. The performance for both the LPG and FBG sensors are consistent with strain measurements using an extensometer. Fiber Bragg grating sensors are of particular interest for distributed sensor applications, where gratings can be addressed using time- and wavelength-division techniques to provide strain distribution along a structural component. Strain readings are obtained from a number of multiplexed sensors which are bonded to the reinforcement, free floating in the concrete, and embedded in composite materials attached to the concrete. A critical issue in developing a optical fiber strain gage is its codependency on temperature and strain. Any changes in the output of the optical fiber sensor due to its own thermal sensitivity and the thermal expansion of the host material will be misinterpreted as a change in shape-induced strain in the structure. This codependence is often referred to as thermally induced apparent strain, or simply apparent strain. Davis *et al.* demonstrated a prototype to evaluate the thermally induced strain in optical fiber sensors embedded in cement-based composites.(66) The effects of thermal induced strain on embedded optical fiber were measured with a white-light fiber-optic Michelson sensing interferometer for a number of cement-based host materials. Maaskant *et al.* successfully demonstrated fiber-optic Bragg grating (FBG) sensors for bridge monitoring in the year 1997.(67)

6.8 *Ribbonlike sensors*

The application of magnetically soft ribbonlike sensors for the measurement of temperature and stress, as well as corrosive monitoring, is based upon changes in the amplitude of the higher-order harmonics generated by the sensors in response to a magnetic interrogation signal. The sensors operate independently of mass loading and can be placed or rigidly embedded inside nonmetallic, opaque structures such as concrete or plastic. The passive harmonic-based sensor is monitored remotely through a single co-planar interrogation and detection coil. Effects due to the relative location of the sensor are eliminated by tracking harmonic amplitude ratios, thereby enabling wide-area monitoring. The wireless, passive, mass-loading independent nature of the sensor platform makes it ideally suited for long-term structural monitoring applications, such as measurement of temperature and stress inside concrete structures.

A new sensor platform is described by Ong and Grimes,[68] capable of remote query measurement of stress and temperature. Operation is based upon relative changes in the harmonic signature of the magnetically soft high-permeability ribbonlike sensors. A simple skeleton view of the magnetically soft ribbonlike sensor is shown in Fig.6.

Magnetically soft ribbons made with different alloy compositions are now commercially available. Fe, B, Si, C, Ni, Mo and Co are the alloying elements generally used for making the ribbonlike sensor. The sensor has a thickness of about 25–28 μm. The sensors were interrogated by an excitation coil connected to a function generator to generate a magnetic field in series with a Dc power supply used to provide the DC biasing field. A detection coil coplanar with the excitation coil was used to monitor the response of the sensor, with the harmonic amplitudes captured using a spectrum analyzer. A computer was used to automate the experiment.

In contrast to magnetoelastic sensors, which mechanically vibrate, the operating principles of the harmonic sensors are electromagnetic in origin; hence, the sensor can be embedded inside rigid media such as concrete, wood, or plastic. This sensor can monitor temperature within concrete, and stress within a wood laminate. The sensor shows a linear and reversible response to temperature over an operating range of 20–90°C. The sensor has a reversible stress response when the applied stress is low, but the response becomes irreversible when the applied stress exceeds a threshold value. The irreversible stress response allows the harmonic sensor to be used to indicate if a structure has been exposed

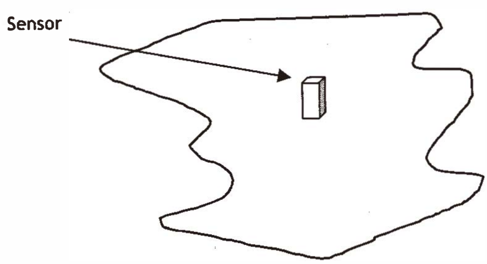

Fig. 6. Skeleton view of ribbonlike sensor.

to too large a stress level that might indicate internal structural damage.

The harmonic sensor has an irreversible response to bleach, in that it dissolves. Chlorine, which accumulates in concrete from applied roadway salt, is an important agent in degrading concrete roadways. Hence, in addition to stress and temperature, the harmonic sensors might find utility in announcing dangerous levels of chlorine in road-beds, bridge decks, etc. It should be noted that the sensor is capable of operating while surrounded by rebar which, although ferromagnetic, is not sufficiently magnetically soft to support higher-order harmonics.

As needed, the sensor can be used on a disposable basis since the sensor has a relatively small unit cost.

6.9 *Covercrete sensors*

The performance of the surface zone is acknowledged as a major factor governing the rate of degradation of concrete structures. The cover of the reinforcement provides the only barrier to aggressive agents that either attack the concrete directly or initiate corrosion of the reinforcement. The water (liquid and vapour) and gas permeation properties of cover-zone concrete (i.e., the covercrete) as durability indicators, and terms such as permeability, sorptivity and diffusion are used in this respect.

Permeation characteristics of concrete have been extensively studied under controlled laboratory conditions, and a variety of testing techniques have been developed and employed by McCarter *et al.*[69–72] It cannot be said, however, that these techniques have been successfully transferred to the field. For example, the dependence of surface-applied techniques (*e.g.* the initial surface absorption test [ISAT]) on the current and previous moisture state of the covercrete has precluded their direct application to field concrete. While laboratory tests are designed to determine individual permeation properties (diffusion coefficient, permeability, sorptivity), in reality, mass-transport and flow processes may be coupled and the dominant processes depend on the exposure and the time of year.

Three broad levels of monitoring are designated low, medium and high, and the appropriate level of monitoring must be considered at the design stage.[73] For example, in the case of severe environmental conditions, long design life and sensitive structures, a high level of monitoring may be the most cost-effective approach. The installation of sensors within the cover zone could thus form part of a high-level program. Because measurements are to be taken over an extended period of time, long-term stability of the sensor system is an important consideration. The schematic of sectional view of embedded covercrete array sensor is shown in Fig. 7.

Figure 7 shows the positioning of rebars, SS counter electrode and covercrete array within the concrete block. All the cable connections from individual electrodes were taken into watertight glass-reinforced plastic (GRP) box. A covercrete array electrode within the surface zone was always placed at the center of the working face of the specimen. The array allows the electrical conductance of the concrete to be evaluated at 5 mm intervals through the surface 50 mm. Also mounted on each array were four thermistors, thereby allowing evaluation of temperature profiles with the cover region.

The simplest sensor arrangement allows electrical measurements to be taken within the cover-zone concrete. Such measurements are technically easy to obtain and can be

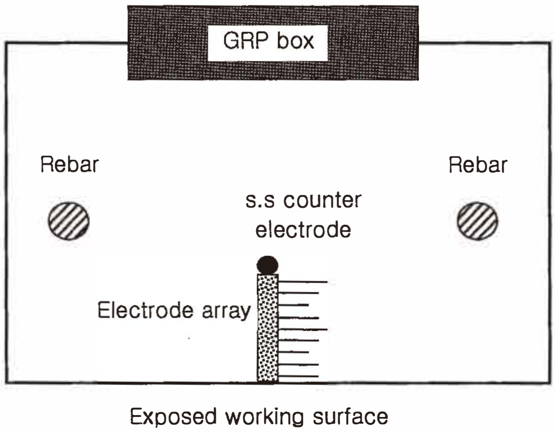

Fig. 7. Sectional view of covercrete array into the concrete.

presented in a range of formalisms —resistance, resistivity, conductance and conductivity. It is important to distinguish beween these different representations and their interrelationship with cement microstructure and environment.

6.10 *Humidity sensors*

Humidity sensors are currently used for corrosion monitoring applications. Humidity is a well-known basic factor in reinforcement corrosion in concrete structures; the development and use of this sensor is essential. Conventionally, water content in concrete was determined from the respective core specimens from different depths. Water content was calculated by the following equation:

$$\text{Water content } (\%) = \frac{M_{\text{as received}} - M_{\text{dry}}}{M_{\text{saturated}} - M_{\text{dry}}} \times 100 \quad (2)$$

The first laboratory results on humidity sensors were reported by Babler *et al.*[74] in the year 2000 using a multiring electrode. There are two types of humidity sensors available for concrete structures. It consists of a multiring electrode system having either a resistance probe or a capacitance probe. In the first case, the electrical AC resistance between adjacent rings in different depths is recorded. Resistance is indirectly proportional to the humidity of the material and can be used for humidity profiles. The principle of this sensor is that, under completely humidified conditions, the sensors show constant resistance values (in the order of kΩ) at all rings, so no drying out process is expected. On the other hand, if any drying out process of the specimen, which depends on the climate, occurs, humidity is reflected by the increase in resistance at every ring of the multielectrode. In the second case, the capacitance probe is installed into the drilled hole of the concrete and then frequency was measured. Frequency is proportional to the capacitance of the concrete and the capacitance probe gives the average of humidity between the surface and its installation depth. Installed above the reinforcement layer and calibrated correctly, it enables the detection of the humidity front when it passes the depth of the sensor. An increase in frequency with time at the capacitance probes reflects the drying out process of the specimen. It has a shape similar to that of resistance measured at the corresponding rings of the multiring electrode. Thus, both types of sensors are comparable.

This sensor system allows determination of water content in between surface and installation depth over a long period. For confirmation, results from this sensor may be compared to humidity profiles obtained by determination of water content in segments at different depths of concrete cores. The development and perfection of this sensor in the field is under way.

6.11 *Embeddable half-cell sensors*

Embeddable reference electrodes are very useful in corrosion monitoring of concrete structures for long-term monitoring and potentiostatically controlled cathodic protection of reinforcement in concrete. Their use in laboratory work and field exposure tests is advisable for the purpose of ensuring valid exchange of data between laboratory and field work. Essentially, accurate measurements are mandatory for prestressed structures where over protection can be as dangerous as underprotection. The increasing use of remote monitoring also requires that reference electrodes be capable of delivering reliable stable performance over an extended period of time. Use of reference electrodes in concrete presents several challenges. Conventional $Cu/CuSO_4$ electrode can be placed easily on an external concrete surface. However, significant errors can develop because of various factors such as the often large resistance path between the steel and the surface, the presence of junction and streaming potentials, rapid variation with time of the moisture of the concrete near the electrode tip, and overall heterogeneity of the medium. As a result, variations of >100 mV are not uncommon when a surface electrode is moved a few millimeters or when some of the external concrete surface is chipped away. Ideally, an embedded electrode should be placed as close to the steel surface. A perfect embeddable electrode must obey the following conditions: it must be stable, invariant to chemical and thermal changes in concrete, tolerant to climatic conditions and have the ability to pass small currents with a minimum of polarization and hysteresis effects, display long-term performance, be cost effective and result from an environmentally safe manufacturing process. Ag/AgCl reference electrodes are commonly used in concrete structures to measure the rebar potential, but their stability under cold conditions and their long-term performance are still questionable.[75,76] Graphite has also performed satisfactorily in concrete, but this is not thermodynamically a true reference.[77] Commercially available Ti rods activated with mixed-metal oxides was reported as a embeddable sensors for concrete.[78] Manganese dioxide reference electrodes have also been reported,[79] as shown in Fig. 8.

MnO_2 electrodes consist of three compartments, namely, a porous cement bottom layer, a conductive alkaline solution middle layer and a MnO_2 top layer. The entire assembly is

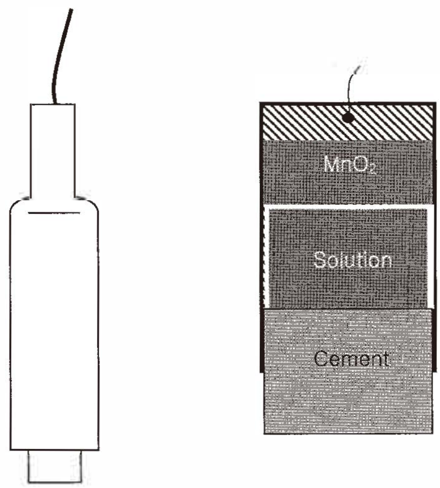

Fig. 8. Structure of MnO_2 electrode.

encapsulated in a thick plastic or a thin stainless steel cover. Initial reports based on MnO_2 reference electrodes are encouraging, but research on the long-term stability of these embeddable electrodes under different environmental conditions is still in progress.

In this respect, the Underground System Group of the Korea Electrotechnology Research Institute, Korea, is now actively engaged in the research and development of various embeddable sensors for the corrosion monitoring of concrete structures.

7. Conclusion

In the future, the development of smart materials and structures will play a major role in all engineering disciplines. The utilization of sensor technology will be one of the most important structural health monitoring and can greatly improve durability and substantially improve the safety of the structure. As such, sensors have been placed in different structures and environments, providing interesting data on the corrosion behavior of reinforcements under real on-site conditions. Key parameters of these sensors depend on the concrete material and its compatibility, humidity, chloride content and temperature. Additional investigations on the development of embeddable reference electrodes under conditions of long-term performance are essential. An intelligent procedure for the employment of such sensors and the interpretation of readings can extend the durability of concrete structures enabling people to undertake suitable preventive measures at the appropriate time. As it is, the sensors can be attached or embedded into concrete structures and can be used to evaluate the health of concrete structures. However, more importantly, the measurement philosophy used in the laboratory and real-world applications are very different. In the actual environment, sensor damage may happen easily beause of weathering, rough handling by labourers and the concrete pouring process. Although many successful sensors have been reported in recent years, the use of this sensor technology in practical, real-life civil engineering applications still needs more research to solve several real and practical problems experienced in both existing and new structures.

Acknowledgements

One of the authors (S.M.) thanks CECRI & CSIR, India, for the permission to pursue a postdoctoral fellowship at KERI, Korea. Thanks are also due to KOFST, Korea, for the financial assistance under the Brain Pool Program.

References

1 P. K. Mehta and R. W. Burrows: Concrete International **16** (2001) 57.
2 J. P. Broomfield, P. E. Langford and A. J. Ewins, The Use of a Potential Wheel to Survey Reinforced Concrete Structures, Corrosion Rates of Steel in Concrete, ASTM STP 1065, American Society for Testing and Materials, West Conshohocken, PA., 1990, 157.
3 J. P. Broomfield, The determination of rates of highway bridge deterioration. Rehabilitation and life cycle costing under the strategic highway research program, NACE Corrodible Structures Conference, (Houston, TX: NACE, 1991).
4 J. P. Broomfield, K. Davies and K. Hladky: Cement and Concrete Composites **24** (2002) 27.
5 P. Schiebl and M. Raupach, Instrumentation of structures with sensors-why and how? In: R.K.Dhir and M.R.Jones (Edt.). Proc. of the Concrete in the Service of Mankind Conference, E and EF sponsors, London, 1996, 1–15.
6 N. S. Rengaswamy, S. Srinivasan, T. M. Balasubramanian, Y. Mahadeva Iyer, N. U. Nayak and R. H. Suresh Bapu: Transaction of SAEST. **23** (1998) 207.
7 ASTM C876: Standard Test Method for Half Cell Potentials of Reinforcing Steel in Concrete, American Society for Testing and Materials, West Conshohocken, PA.
8 J. Flis, S. Sabol, H. W. Pickering, A. Sehgal, K. Osseo-Asare and P. D. Cady: Corrosion **49** (1993) 601.
9 S. Feliu, J. A. Gonzalez, S. Feliu (Jr) and M. C. Andrade: ACI Materials Journal. 87M47 Sept/Oct. (1990) 457.
10 E. Escalante, E. Whitenton and F. Qiu, Measuring the rate of corrosion of reinforcing steel in concrete: Final Report, NBS, NBSIR 86-3456, 1986, 1–27.
11 K. C. Clear, Transportation Research Record 1211, Transportation Research Board 86th Annual Meeting, January (Washington, D.C., : TSB), 1989, 28–37.
12 K. Matsuoka, H. Kihira, S. Ito and T. Murata, Corrosion monitoring for reinforcing bars in concrete, ASTM-STP1065, (1991) 103.
13 C. Andrade and Alonso: Construction and Building Materials **5** (1996) 315.
14 J. Mietz and B. Isecke: Construction and Building Materials **10** (1996) 367-373.
15 S. Ahmad: Cement and Concrete Composites **25** (2003) 459.
16 B. Elsener: Cement and Concrete Composites **24** (2002) 65.
17 B. Elsener and H. Bohni, Potential Mapping and Corrosion of Steel in Concrete, Corrosion Rates of Steel in Concrete, ASTM STP 1065, American Society for Testing and Materials, West Conshohocken, PA., 1990, 143–156.

18 K. R. Gowers, S. G. Millard, J. S. Gill and R. P. Gill: British Corrosion Journal **29** (1994) 25.
19 M. I. Jafar, J. L. Dawson and D. G. John, Electrochemical Impedance and Harmonic Analysis Measurements on Steel in Concrete, Electrochemical Impedance: Analysis and Interpretation, ASTM STP 1188, American Society for Testing and Materials, West Conshohocken, PA, 1993.
20 J. Flis, H. W.Pickering and K. Osseo-Asare: Corrosion **51** (1995) 602.
21 S. Muralidharan, V. Saraswathy, K. Thangavel and S. Srinivasan: Journal of Applied Electrochemistry **30** (2000) 1255.
22 V. Saraswathy, S. Muralidharan, R. M. Kalyanasundaram, K. Thangavel and S. Srinivasan: Cement and Concrete Research **31** (2001) 789.
23 V. Saraswathy, S. Muralidharan, K. Thangavel and S. Srinivasan: Advances in Cement Research **14** (2002) 9.
24 V. Saraswathy, S. Muralidharan, K. Thangavel and S. Srinivasan: Cement and Concrete Composites **25** (2003) 673.
25 V. Saraswathy, S. Muralidharan and S. Srinivasan: Materials Engineering **14** (2003) 261.
26 R. Selvaraj, S. Muralidharan and S. S rinivasan: Structural Concrete **4** (2003) 19.
27 U. Guth, W. Oelbner and W. Vonau: Electrochimica Acta. **47** (2001) 201.
28 P. Schiebl and M. Raupach: Concrete International **7** (1992) 52.
29 M. A. Ilyushchenko and A. V. Danilenko: Sensors and Actuators B **44** (1997) 542.
30 M. Raupach and P. Schiebl: NDT & E International **34** (2001) 435.
31 Anode-ladder-system for corrosion monitoring- Specifications, 05/03, S + R SENSORTEC GMBH, Germany, P.10.
32 D. W. Cullington, P. MacNeil, Paulson and J.Elliott: NDT & E International **34** (2001) 95.
33 M. Ohtsu and H. Watanabe: Construction and Building Materials **15** (2001) 217.
34 R. J. Kirkpatrick, P. Yu, X. Hou and Y. Kim, Interlayer structure, anion dynamics, and phase transitions in mixed-metal layered hydroxides: variable temperature ^{35}Cl NMR spectroscopy of hydrotalcite and Ca-aluminate hydrate (hydrocalumite): Am. Mineral. 84 (1999) 1186.
35 R. J. Kirkpatrick, P. Yu and A. Kalinichev, Chloride binding to cement phases: exchange isotherm, ^{35}Cl NMR and molecular dynamics modeling studies. In: Calcium Hydroxide in Concrete Mater. Sci. Concr. (Special Volume) (2001) 77.
36 P. Yu and R. J. Kirkpatrick: Cement and Concrete Research **31** (2001)1479.
37 F. J. Cano, T. W. Bremner, R. P. McGregor and B. J. Balcom: Cement and Concrete Research **32** (2002) 1.
38 H. Yun, M. E.Patton, J. H. Garrett Jr., G. K. Fedder, K. M. Frederick, J. J. Hsu, I. J. Lowe, I. J. Oppenheim and Paul J. Sides: Cement and Concrete Research **34** (2004) 379.
39 M. A. Climent-Llorca, Estanislao Viqueira-Perez and Ma Mar Lopez-Atalaya: Cement and Concrete Research, **26** (1996) 1157.
40 L. Yang, N. Sridhar, O. Pensado, and D. S. Dunn: Corrosion **58** (2002) 1004.
41 I. M. Shohet, C. Wang and A. Warszawski: Automation in Construction **11** (2002) 391.
42 British Standard Institute BS: 1881, Testing concrete Part 204, Recommendations on the use of electromagnetic covermeters, 1988a.
43 J. H. Bungey and S. G. Millard, Testing of Concrete in Structures, Chapman & Hall, Glasgow (1996).
44 D. A. Chamberlain: Automation in Construction **1** (1992) 71.
45 J. E. McFee, R. O. Ellingson, J. Elliott and Y. Das: IEEE Trans. Instrum. Meas. **45** (1996) 153.
46 U. B. Halabe: Proceedings of the 14th Structures Congress on Building an International Community of Structural Engineers **2** (1996) 812.
47 British Standard Institute BS: 1881, Part 205, Recommendations for radiography of concrete, 1988b.

48 K. R. Lauer: Magnetic/electrical methods, CRC Handbook on Nondestructive Testing of Concrete, eds. M. Malhotra and N. J. Carino, (CRC Press, NJ, 1991) p. 203.
49 B. Glisic and N. Simon: Cement and Concrete Composites **22** (2000) 115.
50 G. Batis and Th. Routoulas: Cement and Concrete Composites **21** (1999) 163.
51 S. Wen and D. D. L. Chung: Advances in Cement Research **15** (2003) 119.
52 P. W. Woei and D. D. L. Chung: Composites Part B **27B** (1996) 11.
53 J. Bydzovsky, L. Kraus, P. Svec, M. Pasquale and M. Kollar: Sensors and Actuators A **110** (2004) 82.
54 W. Ricken, J. Liu and W. J. Becker: Sensors and Actuators A **91** (2001) 42.
55 S. A. Klink: Cement and Concrete Research **4** (1974) 223.
56 R. Mostafiz, Chowdhury, C. James and Ray: NDT & E International **36** (2003) 237.
57 W. Moerman, L. Taerwe, W. DeWaele, J. Degrieck and R. Baets: Structural Concrete **2** (2001).
58 K. T. Lau: Magazine of Concrete Research **55** (2003) 19.
59 L. Yuan, L. M. Zhou, W. Jin, K. T. Lau and C. K. Poon: Optical Fiber Technology **9** (2003) 95.
60 L. Yuan, Q. Li, Y. Liang, J. Yang and Z. Liu: Sensors and Actuators A **94** (2001) 25.
61 L. Yuan, W. Jin, L. M. Zhou and K. T. Lau: Sensors and Actuators A **93** (2001) 206.
62 K. T. Lau, C. C. Chan, L. M. Zhou and W. Jin: Composites Part B **32** (2001) 33.
63 A. L. Kalamkarov, D. O. MacDonald, S. B. Fitzgerald and A. V. Georgiades: Composite Structures **50** (2000) 69.
64 F. Ansari: Cement and Concrete Composites **19** (1997) 3.
65 M. Vries, V. Bhatia, T. D'Alberto, V. Arya and R. O. Claus: Engineering Structures **20** (1998) 205.
66 M. A. Davis, D. G. Bellemore and A. D. Kersey: Cement and Concrete Composites **19** (1997) 45.
67 R. Maaskant, T. Alavie, R. M. Measures, G. Tadros, S. H. Rizkalla and A. G. Thakurta: Cement and Concrete Composites **19** (1997) 21.
68 K. G. Ong and C. A. Grimes: Sensors and Actuators A **101** (2002) 49.
69 W. J. McCarter, T. M. Chrisp, A. Butler and P. A. M. Basheer: Construction and Building Materials **15** (2001) 115.
70 W. J. McCarter, M. Emerson and H. Ezirim: Magazine of Concrete Research **47** (1995) 243.
71 W. J. McCarter, H. Ezirim and M. Emerson: Magazine of Concrete Research **48** (1996) 149.
72 W. J. McCarter, A. Butler, T. M. Chrisp, M. Emerson, G. Starrs and J. Blewett: Structure and Buildings **146** (2001) 295.
73 W. J. McCarter, T. M. Chrisp, H. Ezirim and P. A. M. Basheer: Proc. of the Concrete Repair, eds. R. K. Dhir and M. R. Jones (Rehabilitation and Protection Conference, Dundee, 1996) p. 113.
74 R. Babler, J. Mietz, M. Raupach and O. Klinghoffer: Smart structures and materials, 2000, ed. Liu, S.C. (Proc. of SPIE, 2000) **3988**.
75 H. C. Schell and D. G. Manning: Corroison/85 **263** (Houston, TX, NACE 1985).
76 J. E. Bennett and T. A. Mitchell: Corrosion/92 **191** (Houston, TX. NACE 1992).
77 Use of reference electrodes for atmospherically exposed reinforced concrete structures, NACE Technical Committee Report 11100, March 2000.
78 P. Castro, A. A. Sagues, E. I. Moreno, L. Maldonado and J. Genesca: Corrosion, **52** (1996) 609.
79 H. Arup and B. Sorenson: Corrosion/92 **208** (Houston, TX. NACE 1992).