(i) Weather stations (Section 5.9) capture the atmospheric conditions at the structure. Weather stations are often equipped with anemometers (wind speed), barometers (atmospheric pressure), humidity sensors, air temperature sensors, pyranometers (solar radiation), rain gauges, and other related technology.

The entities these sensor technologies measure are also summarized in Table 3.1.3.

## 5.1—Chloride ion sensors

Concrete infrastructure relies on steel reinforcing bars and prestressing strand for structural capacity (strength and ductility). The penetration of outside chemicals, such as the chloride ion (Cl<sup>-</sup>), promotes premature corrosion of the reinforcing steel in structural concrete, compromising structural capacity and shortening service life.

**5.1.1** *Physical basis and property inferred*—Current methodologies to determine chloride ion penetration into a concrete structure are time-consuming and destructive. Core samples need to be taken to investigate the chloride content of the concrete and at the surface of the reinforcing steel. In addition to being potentially damaging to the structure, this work requires lane closures, causes traffic delays, and puts maintenance crews and the traveling public at risk. The annual direct cost of corrosion in the United States to structural concrete is significant. For the case of corrosion damage in concrete bridge decks alone, it is estimated that an additional \$8 billion annual investment is needed over the next 10 years to improve the condition of the U.S. inventory to one of good repair (Gucunski et al. 2017).

Embedded sensing technology provides an opportunity to monitor internal chloride ion concentration within hardened concrete. The corrosion system inside of structural concrete is complex and depends on many variables that are challenging to control or anticipate. Because of this complexity, these sensors solely focus on detecting the ingress of chlorides into concrete between the surface of the concrete and the reinforcing steel. It should be noted that the rate of mass loss of the reinforcing steel is not directly monitored. Nevertheless, the information from these sensors can allow owners to change the ways deicing salts are applied to their structure, provide guidance about the type and location of protective coatings, and allow for accurate service life predictions to be made while minimizing assumptions. This information is helpful to plan and budget for future repairs and ensure that their concrete infrastructure performs as desired.

In this chapter, chloride sensors that use electrochemical principles and fiber optics, and passive sensors with wirebased triggers as bases, are summarized. Electrochemical sensors, as the name indicates, make use of electrical and chemical principles to measure the chloride ion content. Fiber-optic sensors, on the other hand, are bespoke sensors manufactured such that responses from sensors are calibrated for measuring the quality of chloride ion content. The wire-based triggers provide a simple and inexpensive approach where the resistivity of thin trigger wires of known chemistry is monitored over time. When the chloride ions reach the wires and cause corrosion, the wires will break and the resistivity change is measured.

5.1.1.1 Electrical-based chloride sensors—A well-known chloride ion sensor uses electrical measurements based on silver electrodes with silver chloride (AgCl) coating, which makes use of the soluble nature of AgCl (Atkins et al. 1996; Montemor et al. 2006). A combined chloride and resistivity sensor element is also available for monitoring free chloride concentrations and the electrical resistivity (COST 509 1997). In this sensor, the potential of the embedded chloride sensor is measured relative to the MnO<sub>2</sub> reference electrode (Bertolini et al. 2004). Another patented chloride ion sensor technique includes a pair of electrodes and a polymer film imprinted for chloride ions under alkaline conditions (Murray et al. 2005). The polymer film (methylpyrrole) is deposited on at least one electrode of the pair, which allows measurements in wet or dry media. The electrical conductivity of polymer film depends on the amount of chloride ions taken up by the film.

5.1.1.2 Fiber-optic chloride sensors—Fiber-optic (FO) 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), as well as changes-in-refractive-index-based (Tang and Wang 2007). Most of these methods are nonreversiblebased 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<sub>3</sub>), which reacted with NaCl, forming a white precipitate of AgCl, and this change in color was sensed and related to concentration of chlorides. Reflection- and absorption-based sensors were also reported in the same paper using silver chromate powder. These methods are nonreversible and, hence, the sensors could be used for monitoring cumulative chloride concentration reaching the level of sensors. Another similar work was reported by Fuhr et al. (1997), where the technique was modified by using dichloroflouroscein dye that changes color from pink to milky white depending on the concentration of positive charged silver ions in AgNO<sub>3</sub> solution. These sensors were embedded in various bridge deck slabs and had also been used as chloride threshold indicators in concrete structures (Fuhr and Spammer 1998; Fuhr and Huston 2000).

A sol-gel based fiber-optic chloride sensor has been developed by Xie et al. (2004) and McPolin et al. (2011). 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 600  $\mu$ m (0.02 in.) silica fiber using an epoxy adhesive and then covered with protective sheathing, as shown in Fig. 5.1.1.2a. The calibration graph obtained at chloride concentrations of 1, 2, and 3 percent with silver nitrate indicator is shown in Fig. 5.1.1.2b. This investigation has shown the scope for potential use of sol-gel material as an interactive membrane containing chloridesensitive indicator, which could be used for monitoring chloride content in concrete structures. Further research in





*Fig. 5.1.1.2a—Sol-gel based chloride sensitive fiber-optic (FO) probe (Xie et al. 2004; McPolin et al. 2011).* 



Fig. 5.1.1.2b—Calibration of sol-gel based chloride probe using silver nitrate as indicator (Xie et al. 2004; McPolin et al. 2011).

this area is needed to explore chloride-sensitive indicators, which are reversible in nature.

Another chloride sensor has recently been reported (Lam et al. 2009), which is based on fluorescence quenching using Lucingenin indicator dye encapsulated in sol-gel (Laferriere et al. 2008). This sensor showed a linear correlation between the intensity ratio and chloride concentration. In this study, the sensors were embedded in mortar samples at different depths and the free chloride concentrations were monitored while the mortar blocks were subjected to marine environmental conditions.

More specific details about FO measurements can be found in Section 4.5.

**5.1.1.3** Passive radio frequency identification (*RFID*) sensors with wire-based triggers—Wire-based triggers provide an economical sensor that uses wires that closely match the chemistry of the reinforcing steel used in concrete. Simple resistivity measurements are used on these wires over time to measure the change in cross-sectional area of the wire as they corrode. Wires of different sizes have been shown to corrote in concrete at repeatable chloride concentrations (Materer et al. 2011b, 2013). Examples are shown in Fig. 5.1.1.3a.



Fig. 5.1.1.3a—Chloride diffusion profile for concrete sample with wire-based triggers. The depths of the embedded 0.125 and 0.065 mm ( $5 \times 10^{-3}$  and  $2.5 \times 10^{-3}$  in.) diameter wires are shown by the solid vertical lines. The solid lines are the chloride diffusion profiles for concrete samples with the embedded 0.125 mm ( $5 \times 10^{-3}$  in.) wires while the dashed lines are the profile for concrete embedded with 0.065 mm ( $2.5 \times 10^{-3}$  in.) wires (Materer et al. 2013). (Note: 1 mm = 0.394 in.)



Fig. 5.1.1.3b—Completed RFID wire-based chloride sensor. Two sensing wires are shown on the outside of the sensor (Materer et al. 2013).

Next, these wire-based triggers had been combined with radio-frequency identification (RFID) technology to allow them to be measured using a wireless antenna (Materer et al. 2013; Pour-Ghaz et al. 2013). The use of RFID platforms for structural health monitoring shows great promise. A standard RFID tag, consisting of a RFID device or integrated circuit, a capacitor, and receiver coil, is inexpensive, wireless, and requires no internal power. This means that the sensor would not need a battery and can be read by typically passing an antenna over the surface. For this application, the typical RFID circuit had been modified so that it changes the response based on the resistivity of the trigger wires (Materer et al. 2013). These trigger wires are outside of the circuit and placed directly in the concrete. The current sensor is 25 mm (1 in.) in diameter and 10 mm (0.4 in.) thick. An image of the available ensor that uses two trigger wires is shown in Fig. 5.1.1.3b.





Fig. 5.1.2—Test equipment required for fiber optic sensors (McPolin et al. 2009).

**5.1.2** Equipment needed—In general, fiber-optic (FO) measurement techniques require a light source and appropriate FO cable with chemical probe tip. A spectrophotometer calculates the light absorption (McPolin et al. 2009); refer to Fig. 5.1.2. An analog-to-digital (AD) converter and a computer is often used to measure, interpret, and store the data. In mixed metal oxide (MMO) electrode technique, specific carefully treated electrodes are necessary. Several chemical processes such as thermal oxidation and aging in pure water may be needed for sensor preparation (Du et al. 2006). The RFID sensors are powered by a magnetic field and the radio frequency receiver (Materer et al. 2013). More specific details about FO measurements can be found in Section 4.5.

5.1.3 Method of deployment-All these sensors can be embedded directly in the concrete in the region above or nearby the reinforcing steel during initial construction or at the time of a repair. The sensors should be placed at several known depths and locations within the concrete; furthermore, it is recommended that the sensors be placed at several, incrementally increasing depths from the surface so that the progression of the chloride ion front can be monitored over time. For the case of existing structures, cores taken from the position to be monitored may be instrumented with inserted sensors, accommodated by drilling small holes in the core surface. Then the core is remounted at its original position in the structure (Bertolini et al. 2004). To ensure reliable chloride ion measurement capability, the long-term stability of each sensor should be tested before they are applied to in-place monitoring (Du et al. 2006).

**5.1.4** *Strengths and limitations*—Although AgCl electrical sensors are effective and practical for field use, they suffer from several limitations, such as limited longevity of Ag/AgCl electrodes, influence of temperature and pH on measurements, and the influence of other ions such as bromide ions present in seawater (Atkins et al. 1996). Furthermore, Ag/AgCl electrodes are insensitive to low chloride ion concentration and must be wet to allow the chloride ions to be mobile at the time of measurement. Polymer

film electrical sensors can measure chloride ion concentration both in wet and dry media and across broad pH range, but these sensors are nonreversible and, thus, only measure the total accumulation of chloride ions.

Fiber-optic sensors are relatively small in their size and are lightweight. Also, they are immune to electromagnetic interference and have good multiplexing (ability to integrate several sensors at once) capability. However, sol-gel based FO sensors may not be suitable for long-term chloride monitoring in concrete owing to the nonreversability of the chemical reaction between the chloride ions and the indicator in the sol-gel.

The RFID wire-based sensors are inexpensive, can communicate wirelessly, and do not require power to be supplied to the sensor with batteries or wires—this is a great strength for the sensor. Because of their low cost and ability to be measured easily, these sensors can be used in much larger numbers and to measure at different depths. This would allow an owner to receive a constant update on the ingress of corrosive chemical species into their structure. Also, these sensors will measure the potential for corrosion from any external ion and not just chlorides.

A limitation of all chloride ion sensors is that they can only measure the location where they are located. This means that if there is a large crack that forms that allows chlorides into the structure and the chloride sensor is not there locally, chloride ingress could very well not be detected. Further, nearly all these sensors are designed to be deployed in freshly placed concrete; thus, they cannot be used on existing structures. In addition, because of the complex chemistry of the pore solution within concrete, some specific testing may need to be done with the sensors in the proposed concrete mixture to determine how the sensor will respond; broader usage and more experience with these sensors may obviate this problem. To combat all these limitations, it is recommended that chloride sensors be used in combinations with other SHM techniques on structures. It is through a combination of methods that most useful and reliable data can be obtained for a structure.

Table 5.1.4 summarizes the strengths and limitations of the different types of chloride ion sensors.

**5.1.5** Availability and readiness for application in the field—Although some commercial chloride ion sensors do exist in the market, a broad selection of different sensors are still not available. However, the RFID wire-based sensors are ready and available for application in the field. These sensors have been used on six different bridge structures in three different states in the United States. Robustness testing of the sensors has also been completed that investigated temperature, loading, and cracking potential caused by the sensors (Materer et al. 2011a).

**5.1.6** Available standards and codes of practice—No test standards or codes of practice are available with regard to implementing chloride ion sensors in concrete structures.

## 5.2—Corrosion sensors

**5.2.1** *Physical basis and property inferred*—Corrosion is an electrochemical process that involves a set of coupled

aci

Description	Strengths	Limitations
Electrical-based chloride sensors	(a) Effective for practical field application	<ul> <li>(a) Limited longevity of electrodes</li> <li>(b) Sensitive to temperature and pH variations</li> <li>(c) Require fluid to allow flow of ions</li> <li>(d) Polymer film sensors work under wet and dry conditions</li> <li>but provide a cumulative measurement</li> <li>(e) Local measurement</li> </ul>
Fiber optic chloride sensors	<ul><li>(a) Insensitive to electromagnetic interference</li><li>(b) Ability to multiplex—that is, allowing for measurements along the length of the FO wire</li></ul>	(a) Sol-gel based sensors undergo nonreversible reaction with chlorides and, thus, have limited application for long-term monitoring
RFID sensors	<ul><li>(a) Inexpensive</li><li>(b) Communicate wirelessly</li><li>(c) Passive—that is, do not require power supply to the sensor</li></ul>	

Table 5.1.4—Summary of strengths and limitations of chloride ion sensors

reduction-oxidation reactions. The reactions take place at surface locations on one or more metals that are electrically connected by a conductor (often the metal itself). At one surface location, the anodic reaction causes the oxidation (dissolution into ionic form) of metal and release of electrons. At another surface location, the complementary cathodic reaction causes reduction of water and oxygen and consumption of the electrolyte, is also required as a bridge between the two reaction sites to support transport of ions. The four elements in concert (conductor, electrolyte, anode, and cathode) form an electrochemical cell. Further information about corrosion of metals in concrete can be found in ACI 222R.

The sensors discussed in this section characterize corrosion activity, or the potential for such activity, within reinforced concrete elements. Embedded electrodes that protect against corrosion—for example, through cathodic protection—are not considered in this chapter. Several different phenomena are used as bases for the various types of corrosion sensors, although all are connected to electrochemical measurements and behavior. In this chapter, six phenomenological bases are addressed: electrochemical half-cell potential (HCP); linear polarization resistance (LPR); electrochemical impedance spectroscopy (EIS); galvanostatic pulse (GP); macrocell current (MC); and sacrificial sensors (SS).

In the half-cell potential (HCP) technique, an electrochemical cell is established between the working electrode (the steel embedded in concrete) and an external reference half-cell. The resulting voltage difference between the two half-cells can be used to determine the likelihood of active corrosion, though actual rate of corrosion is not indicated by this method.

In the linear polarization resistance (LPR) technique, small electrical perturbations to a corroding system are applied, and the resulting electrical response is monitored (Bohni 2005). For example, incrementally increasing levels of DC electrical current are applied to the corroding system, and the resulting over-potentials are measured at each current level. The ratio of resulting over-potential to applied current as the applied current tends toward zero (the unperturbed state) is called the polarization resistance  $R_P$ . The Stern-Geary equation is used to interpret  $R_P$  values; the equation

states that  $R_P$  is inversely proportional to the active corrosion current density of the corroding element, or working electrode, through the Stern-Geary constant *B* (Ahmad 2003). The active corrosion rate of the working electrode is then evaluated from the corrosion current density with empirical guidelines (Berke et al. 1990).

In the electrochemical impedance spectroscopy (EIS) technique, an AC over-potential, having frequencies varying across a broad range (Hz to MHz), is applied to perturb the corroding system of the working electrode, and the resulting current density is measured (Bohni 2005). By analyzing the real and imaginary components of the impedance spectrum, the complex ohmic resistance of the concrete is determined and it is then used to estimate the corrosion state at the working electrode by comparing it with the value obtained at a noncorroding state.

In the galvanostatic pulse (GP) method, a constant electrical current pulse is applied to the corroding working electrode, and the over-potential transient response is measured during some time period; a typical constant pulse duration can be up to 10 seconds. The  $R_P$  value of the corroding system is then obtained using curve-fitting methods or linearization procedures (Song and Saraswathy 2007). The obtained  $R_P$  is then used to indicate the corrosion rate of the working electrode in a similar fashion as the LPR method.

Macrocell current (MC) sensors are passive, meaning that electrical perturbation of the corroding system is not needed. Rather, electrical currents between the established anode and cathode in a corrosion process are monitored. Cathodeanode separation is typically the result of relative exposure. For steel embedded in concrete, the anode is initiated either by reduced pH near the metal surface (for example, caused by carbonation) or by corrosion pits at the metal surface resulting from chloride ion attack. The cathode forms at another surface location in electrically connected elements that are not directly subject to attack, but have an ample source of oxygen to support the associated cathodic reactions (Raupach 1996). Increasing levels of macrocell current indicate active corrosion between the measurement points.

Sacrificial sensors (SS) indicate the corrosive level of the environment in which they are embedded. These sensors monitor the corrosion of a sacrificial element within the sensor itself, thus indicating the nature of the environment



that surrounds the sensor. However, they do not directly indicate the corrosion condition of the structural element of interest (for example, embedded reinforcement).

**5.2.2** Equipment needed—For the HCP method, a reference half-cell, conductive wire, and voltmeter are required. The reference half-cell is composed of a specific metal electrode-electrolyte solution combination with an ionically conductive medium (often a porous ceramic or other material) to bridge to the external electrolyte in the system of interest. Reference half-cell electrodes, such as Cu-CuSO<sub>4</sub> or Ag-AgCl, each have a known electrical potential, against which measurements are made in the cell with the voltmeter. More information about the HCP method can be found in ACI 228.2R. Often, solid reference electrodes are used in embedded configurations. This type of reference cell is often employed in more advanced techniques such as LPR, GP, and EIS to establish the open-circuit potential and monitor perturbations of the system.

For LPR, a potentiostat drives the electrical interrelation among the reference, counter, and working electrodes, as shown in Fig. 5.2.2, where the working electrode (the corroding element) is perturbed from its equilibrium state. In modern systems, an analog-to-digital (AD) converter and a control computer are necessary to measure, interpret, and store the corrosion-induced currents (Bohni 2005). First, a potentiostat applies a constant potential to the steel reinforcement in concrete. The resultant current is measured after the perturbed system reaches stationary conditions.

For EIS, the necessary equipment is similar to the LPR technique: a potentiostat, reference and test cells, an AD converter, and a control computer (ASTM G106; Bohni 2005). The difference between the EIS and LPR methods is that AC electrical currents of varying frequency are applied to the system. For the GP method, similar equipment to that used in LPR is needed, except that a controlled constant current source is needed.

MC sensor systems require artificial anodes and voltmeters (or ampere meters) to monitor the macrocell currents. MC is a passive system, so no external electrical perturbation to the corroding system is required. SS systems are typically selfcontained units, so no additional hardware is needed.

5.2.3 Method of deployment—The HCP, LPR, EIS, and GP methods are often applied as nondestructive tests to manually measure potential or corrosion along the exterior surface of a reinforced concrete element. However, these methods, as well as MC and SS, can also be applied in a permanent structural health monitoring configuration using sensors and electrodes embedded in concrete adjacent to the metals of interest (for example, reinforcing steel). An early type of MC sensor that could be embedded in concrete was the anode ladder system (Raupach and Schiessl 2001), which can be used to monitor the risk of corrosion as a function of cover depth. In the anode ladder system, a housing that contains series of plain carbon steel rod anodes that are arranged parallel and with increasing depth from the concrete surface is embedded in concrete. Each of the anodes is electrically connected to a noble cathode, usually composed of stainless steel, also embedded nearby; the galvanic corrosion currents



*Fig. 5.2.2—Illustration of LPR test configuration (Bohni 2005).* 

between each of the individual anodes and the cathode are then monitored continuously monitored. Once one of the steel anodes becomes depassivated-for example, because of carbonation or chloride ion transport to that depththe galvanic corrosion current between that anode and the cathode increases markedly. Thus, the time rate of depassivation with depth is monitored, and from several measurements, the time required for the depassivation front to travel through the cover concrete and reach the top layer of steel reinforcement can be predicted. Note that this sensor system does not monitor the corrosion of the reinforcing steel itself. More recently, embedded LPR sensors have been deployed in large reinforced concrete beams; however, the nonuniform distribution of electric signal throughout the cross section of the beam should be considered (Feliu et al. 1988). For microcell current and sacrificial sensors, distributed artificial anodes are installed directly on reinforcing bars in concrete during the construction phase prior to casting. Reinforcing bar mats can also be mechanically cut to separate local anodes and cathodes from already constructed reinforced concrete specimens. Internally shunted voltmeters (or ampere meters) are installed between bar sets to measure macrocell currents and, thus, to evaluate corrosion state of the target structure, as shown in Fig. 5.2.3.

**5.2.4** *Strengths and limitations*—HCP is a simple technique that can be used to monitor the relative corrosion activity of embedded metals in concrete over time. While HCP does not relay specific corrosion rate information, HCP is still a useful indicator. However, long-term stability and durability of embedded half-cells containing solutions may be a concern, so solid electrodes may be preferred (Duffó et al. 2009; Pawlick et al. 1998).

The principal advantages of the LPR technique are that it allows instantaneous corrosion rate estimates of the working electrode. The sensor hardware is available at a reasonable price. The technique does not necessarily require significant damage to concrete samples in the case of embedded sensor packages. However, these embedded sensor packages typically monitor the corrosion of an internal working electrode within the sensor, not the reinforcing steel of interest; in this case, the sensors act more like a sacrificial type of sensor. To monitor the reinforcing steel directly, a direct electrical connection must be made to the steel element, which

(aci)



Fig. 5.2.3—Illustration of embedded MC sensors within steel-reinforced concrete element (Raupach 1996).

requires some level of concrete destruction in the case of existing structures. Corrosion current density estimates from this technique also will be influenced by the assumed surface area of reinforcing steel that is electrically perturbed during the test. Finally, the estimated corrosion rate is largely dependent on the assumed values of the Stern-Geary constant, which may be inaccurate for varying environmental conditions such as temperature.

The EIS sensing approach provides more detailed information about the corrosion state of the working electrode across a broad frequency range. For example, high-frequency data provide information about dielectric properties of concrete (environment surrounding the working electrode), while low-frequency data reflect the corrosion condition of the working electrode. As with LPR, direct electrical connection must be made to the steel element to monitor the reinforcing steel directly, which requires some level of concrete destruction in existing structures; issues concerning surface area apply as with LPR. Also, the method can be timeconsuming, especially if sweeping across the low-frequency range. Furthermore, it is difficult to analyze the impedance spectrum because this technique is not only sensitive to corrosion of the working electrode, but also to other conditions in the surrounding environment-for example, the presence of cracks in concrete. Finally, it can be difficult to quantitatively estimate the corrosion rate by analyzing the measured impedance spectrum.

The GP method has attributes similar to that of LPR. However, GP offers one benefit over LPR: the method needs a relatively short testing time (10 seconds) to obtain data. However, the response to the input pulse current needs to be stabilized to obtain an accurate value of the polarization resistance. Also, direct electrical connection to the working electrode is necessary.

MC sensors offer benefits over other corrosion-monitoring schemes. MC sensors enable detection of local pitting corrosion in steel. However, MC sensor technology suffers from the difficulty in completely separating anode from cathode, resulting in an underestimation of the corrosion rate. This technique also requires direct contact with the corroding steel reinforcement.

Sacrificial sensors offer the significant benefit that direct connection to the reinforcing steel of interest is not needed. However, these sensors do not directly monitor the corrosion state of the steel elements of interest, but rather monitor the environment surrounding the steel element for its potential to support corrosion processes.

HCP, LPR, EIS, and GP methods are generally not recommended for use to directly monitor the corrosion activity of metals with insulating barrier coatings such as epoxy. The barrier will prevent or alter the expected electrochemical cell and it will be impossible to determine what portion, if any, of the metal is represented by the results. Further, it is important to recognize that the presence of sacrificial metals, such as galvanic anodes or coatings, will influence the electrical potential and response of the system to these various techniques. Such tests should be conducted and interpreted by individuals with specific knowledge and expertise to interpret these influences. However, one or more of the methods may be useful in monitoring—for example, the performance of installed cathodic protection systems.

Table 5.2.4 summarizes the strengths and limitations of the different sensors and techniques to monitor corrosion.

5.2.5 Availability and readiness for application in the field-LPR sensors are widely commercialized (BAC Group 2019; Virginia Technology, Inc. 2019) and have been applied to in-place corrosion monitoring (Berke et al. 1990). The feasibility of the EIS technique to large-scale structures has been validated (Berke et al. 1990), but few commercial sensor systems are available in the market, owing to the complexity of the data analysis required by this technique. Several commercial GP sensors are available (Force Technology 2019; PTCE Inc. 2019), and their applicability to in-place concrete structures has been evaluated (Klinghoffer 1995). Several commercial MC sensors are available in the market (BAC Group 2019; Force Technology 2019), and the long-term applicability of this technique has been studied (Berke et al. 1990). Sacrificial sensors are ready and available for application in the field. Robustness testing of

This is a preview. Click here to purchase the full publication.

Description	Strengths	Limitations
НСР	(a) Simple technique	<ul><li>(a) Relative indicator for corrosion activity</li><li>(b) Solid electrodes preferred due to limited lifetime of half-cells</li><li>(c) Not recommended for use with epoxy-coated reinforcing bars</li></ul>
LPR	<ul><li>(a) Provides instantaneous estimate of corrosion rate</li><li>(b) Relatively inexpensive hardware</li></ul>	<ul> <li>(a) Measurement is indirect via working electrode</li> <li>(b) Connection with steel required for direct corrosion rate estimates</li> <li>(c) Accuracy dependent on selected constants as well as environmental conditions</li> <li>(d) Not recommended for use with epoxy-coated rebars</li> </ul>
EIS	<ul><li>(a) Can provide additional information such as dielectric properties of concrete</li><li>(b) Measurement more involved</li></ul>	<ul><li>(a) Extraction of quantitative corrosion rates from impedance spectra can be difficult</li><li>(b) Not recommended for use with epoxy-coated rebars</li></ul>
GP	(a) Short measurement time (10 seconds)	<ul><li>(a) Direct connection with working electrode required</li><li>(b) Not recommended for use with epoxy-coated rebars</li></ul>
МС	(a) Enable local pitting corrosion	(a) Difficulty in separating anode from cathode, which results in underestimation of corrosion rate
SS	(a) Direct connection to reinforcing steel not required	(a) Measurement provides information regarding concrete environment for corrosion potential

 Table 5.2.4—Summary of strengths and limitations of corrosion sensors



Fig. 5.2.5—Embeddable multi-functional corrosion sensor for new construction (Kelley et al. 2002).

one specific type of sacrificial sensor, which investigated temperature, loading, and cracking potential caused by the sensors, has been completed (Materer et al. 2011b). Multi-function sensor packages, which incorporate more than one sensing technology, are also available. An illustration of implementation of a multifunctional corrosion sensor in new construction is shown in Fig. 5.2.5.

**5.2.6** Available standards and codes of practice—No test standards or codes of practice that directly relate to corrosion sensing in reinforced concrete could be identified. However, ancillary test standards such as that in ASTM G106 do exist. ASTM G106 specifies an experimental procedure that can be used to verify instrumentation and technique for collecting and presenting electrochemical impedance data. This practice provides a standard material, electrolyte, and procedure for collecting electrochemical impedance data at the open circuit or corrosion potential that should reproduce data determined by others at different times and in different laboratories. Similarly, ASTM C876 governs the measurement and interpretation of helf cell potential at leasting of helf cell potential at leasting of

the surface of a concrete element containing uncoated reinforcing steel. While ASTM C876 does not specifically govern use of embedded electrodes, the principles are similar.

## 5.3—Humidity sensors

**5.3.1** *Physical basis and structural property inferred*—Relative humidity (RH) sensors are reviewed in this section. Such sensors include ambient temperature-sensing technology and are therefore also called relative humidity and temperature (RH&T) sensors.

For the purpose of SHM, RH is an environmental measure of moisture in and around the structure of interest. Humidity is a general term used to describe water in vapor phase, held by a gas or gas mixture (Wyer 1906; Wiederhold 1997). RH is a metric to quantify levels of humidity in atmospheric and other environmental gases (Perry and Green 2008). Conceptually, RH is the amount of water vapor being held in a gas with respect to the available space for it within the gas. RH is formally defined as the ratio, for a given temperature, of the partial vapor pressure of a gas to the vapor pressure of that gas if saturated, expressed as a percentage (Wiederhold 1997). One hundred percent RH represents the point at which the rate of evaporation and condensation between liquid and vapor phases at a water surface are in dynamic equilibrium; because vapor pressure is a function of the kinetic energy of the water molecules, the saturation vapor pressure increases with increase in temperature; thus, RH reduces as temperature increases for a fixed amount of water vapor. Within concrete, the saturation vapor pressure is further influenced by surface curvature and, thus, diameter of the pores where such liquid surfaces lie, as menisci of decreasing radius within concrete pores result in lower vapor pressure and RH for a fixed amount of water vapor relative to a flat water surface in an open container (Grasley et al. 2006).

**5.3.1.1** *Primary methods for measuring RH in air*—For example, gravimetric and chilled mirror hygrometers or wet/ dry bulb psychrometers (Fig. 5.3.1.1a) are based on mechan-



ical principles but are not practical for field monitoring applications on concrete. Most of the commercially available sensors used in SHM applications to measure RH employ electrical methods and are classified as secondary devices. The sensors are classified as such because, while their operation relies on a variety of scientific principles, none rely directly on fundamental hygrometric, or psychrometric, principles or use corresponding base units of measure. Rather, the sensor produces a repeatable unique response if exposed to an atmosphere of a given RH, at a given temperature. The response output, which varies among the technologies used, is then correlated over a specified operational range of RH and temperature. While RH is not a direct measure of moisture content, it is a measure of the concentration of water vapor in the concrete, and monitoring the evolution of RH in concrete can be useful to quantify the state of moisture in concrete as correlates to shrinkage or thermal strain (Grasley et al. 2006). Three common examples of secondary sensor types include: capacitive polymer sensors (Fig. 5.3.1.1b), resistive polymer sensors, and fiber-optic sensors (Wiederhold 1997; Yeo et al. 2008), as described below.

a) Capacitive polymer sensors: These sensors operate by measuring the capacitance between two conductor plates separated by a thin film of nonconductive polymer insulation. The thin film selected is hygroscopic with dielectric properties that vary uniquely with adsorbed or desorbed moisture content and temperature. As the dielectric properties change, so too does the measured capacitance. For this type of sensor, the capacitance is the output value, which is correlated to RH.

**b) Resistive polymer sensors:** These sensors operate by measuring the ohmic resistance between anode and cathode leads embedded in a resin containing a semi-conductive, polymerized salt. This hygroscopic resin has conductive properties that vary uniquely with adsorbed or desorbed moisture content for a given temperature. Namely, as the moisture content within the resin increases, its conductivity increases, thereby reducing the measured resistance. For this type of sensor, the resistance is the output value, which is correlated to RH.

c) Fiber-optic sensors: These sensors, in terms of measuring RH, are relatively new. One design operates by passing light through a composite (Fabry-Perot) hygro-scopic filter, which gets transmitted back through a separate receiving fiber-optic line. The refraction indexes of the various layers making up the composite filter are uniquely altered with adsorbed, or desorbed, moisture content, thus causing a shift in the reflected light's (peak) wavelength properties. For this type of sensor, the decoded light shift is the output value which is correlated to RH.

Fiber Bragg grating (FBG)-based sensors are popularly used in structural health monitoring of concrete structures due to their increased sensitivity to strain and temperature (Slowik et al. 1998). Furthermore, the small dimensions of FBGs can be used as microsensors. By applying a calorimetric or size-sensitive chemical coating on FBGs, they can aid in measuring different parameters. This principle was used by Srinivasan et al. (2009) to develop an FBG-



Fig. 5.3.1.1a–Wet/dry bulb psychrometer.



Fig. 5.3.1.1b–Capacitive sensor, shown without a probe housing.

based RH sensor, wherein a moisture-sensitive polymer, which swells with an increase in moisture and thus induces a strain effect, was coated on the grating. Therefore, the RH level is given through the shift in wavelength caused by the expansion of the moisture-sensitive polyimide layer on the Bragg grating. The measurement of RH requires a sensor with both moisture and temperature capabilities, as the RH values should be calibrated against the effects of temperature change. Thus, a FBG-based temperature sensor is placed along with a fiber-optic moisture sensor in a stainless steel tube of 5 mm (0.2 in.) diameter to protect the fiber against damage from manual handling; perforations are made at one end of the tube near the sensor region to allow the moisture flow, as shown in Fig. 5.3.1.1c.

Field verification of the suitability of this design was carried out by Srinivasan et al. (2010) and Smith et al. (2011), wherein complex moisture regime patterns in stone masonry were monitored using the fiber-optic RH sensors. The sensor was found to respond to diurnal and hourly variations in moisture regime caused by external fluctuations in climate conditions. Fiber-optics-based sensors are further discussed in Section 4.5.

**5.3.2** Equipment needed—In practice, field RH&T systems can include manually interrogated portable or embedded sensors or programmable single and multisensor systems. Programmable systems range in size and complexity from single-sensor, self-contained data acquisition (DAQ) systems the size of a nickel to robust multicomponent, multi-sensor array DAQ systems. The user's scope of intended application governs the required system is required, such as a programmable multi-sensor array for use in field, the following will likely be required:

- (a) Sensor
- (b) Probe housing
- (c) Weather-tight enclosures



This is a preview. Click here to purchase the full publication.



Fig. 5.3.1.1c—Fiber-optic RH sensor encased in stainless steel.

- (d) Primary DC power source; solar panels are an option
- (e) Backup DC power source (optional)
- (f) Data-logger
- (g) Multiplexers for multi-sensor arrays
- (h) PC interface and software
- (i) Remote communications (optional)

As all the sensors above rely on the interrogation of hygroscopic materials, they need to be shielded from direct contact with liquid moisture. Some sensors use onboard heating elements that help prevent the formation of condensation. To prevent liquid contact from other sources, sensor housing designs may make use of venting materials, which allow for the approximate free passage moisture in vapor phase only.

**5.3.3** *Method of deployment*—RH sensors may be deployed in a variety of ways, including:

- (a) Embedment in fresh concrete
- (b) Placed, sealed, or both, inside drilled or cast holes
- (c) Placed between material layers

(d) Placed in an open environment, close to a structure of interest

The placement and number of sensors is determined by the application. Each sensor provides data for a discrete location. Several sensors may be needed if a profile or contour of RH is required. Each sensor may require a hole in the structure if embedment is not an option. In field SHM applications, as illustrated in Fig. 5.3.3a, a robust multi-component, multi-sensor array DAQ system might be deployed as follows. The data-logger is contained in a weather-tight enclosure at an accessible location on or near the structure of interest.



Fig. 5.3.3a—Diagram (elevation – top right; section – top left; and close-up – bottom left) of a multi-sensor RH array connected to a DAQ system in a highway bridge deck adjacent to a parapet and rail. The weather-tight enclosure "Box - A" would contain multiplexer with leads to multiple RH sensors. The weather-tight enclosure "Box - B" would contain data-loggers, primary and optional backup power, and optional remote communications.

Depending on the number of RH and other sensors to be monitored, multiplexers may be required and may be collocated with the data acquisition system or placed in the vicinity of the multi-sensor array, depending upon relative proximity of the sensors to one another. Multiplexers also require a DC power source, which may be drawn from the data-logger, provided physical connection is used. Probes containing the RH&T sensors are connected to the DAQ or multiplexer. DAQ systems may be designed to read any number of channels, though common multiplexers handle up to between 16 and 32 sensors.

Other field SHM applications may require a far less robust system. A portable single-sensor system, as illustrated in Fig. 5.3.3b, may be deployed in the following way. A single sensor, or series of single sensors, may be cast or placed inside the concrete structure. A portable data-logger is used to manually interrogate each sensor. If the sensor is programmable, then the values collected may span a userspecified period; if not, then the values would be limited to those taken at the time of interrogation.

**5.3.4** Strengths and limitations—RH sensor accuracy and precision are a function of the sensor and DAQ system designs, which vary between systems. However, for the RH&T sensor alone, it is not uncommon to find economically priced, commercially available sensors with accuracy of  $\pm 2$  percent RH within an operational range from 10 to 20 percent RH at the low end to 80 to 90 percent RH at the high end. If used outside this operational envelope, errors of up to  $\pm 5$  percent RH are possible. In many cases, the manufacturer



of a resistive or capacitive polymer-based sensor will supply a certificate of calibration, traceable to a NIST standard.

RH&T sensors may not be handled like other sensors, as mishandling and exposure to certain environments are likely to either damage the sensor or compromise its calibration. Additionally, long-term exposure to extreme operating conditions—for example, greater than 95 percent RH—are also likely to cause a recoverable shift in response from the calibrated condition.

Resistive and capacitive sensors are generally stable over time and easy to deploy. Each resistive or capacitive sensor requires a pair of individual electrical leads to DAQ or multiplexor channel with voltage excitation to support measurement. By contrast, multiple fiber-optic sensors can be distributed along a single fiber and do not require electrical stimulation at the sensor location. Capacitive film RH sensors generally provide better linearity over a broader range of RH than resistive sensors but take longer to reach equilibrium (stabilize to an accurate reading). Also, many of these types of sensors are relatively economical. In terms of arrays, as described previously, RH&T sensors of either type easily integrate into larger SHM systems containing a wider range of sensor types-for example, strain gauges (Section 4.8), load cells (Section 5.4), and accelerometers (Section 4.10).

This technology has been used for monitoring the effectiveness of membranes and overlay systems applied to



*Fig.* 5.3.3b—Portable, single-sensor system (shown deployed in a slab-on-ground).

concrete bridge decks (White II and Kunin 2010). However, there are at least two obstacles to using the technology in this way. The first obstacle has to do with the initial moisture content of concrete decks in need of an overlay, as there is a definite upper limit to the range of internal relative humidity such a system may practically detect. Second, there are potential errors in the RH data being collected if the structure is exposed to natural weathering and evolving thermal cycles (Andrade et al. 1999). For this reason, more research is needed if the applications involve monitoring the internal environments of in-service structures exposed to weather, such as bridges.

Table 5.3.4 summarizes the strengths and limitations of the different types of humidity sensors.

**5.3.5** Availability and readiness for application in the field—Several types of RH&T sensors are commercially available and commonly used. A variety of manufacturers supply DAQ systems capable of seamlessly accommodating an entire suite of SHM sensor types, including analog and digital RH&T sensors. In some cases, the DAQ systems are even more streamlined than the general one described.

Whether practical implementation is viable depends on the application. The following applications would be considered ready for implementation:

(a) Monitoring the environmental ambient RH in the vicinity of a structure

(b) Determining the internal RH and moisture content of a sheltered concrete floor/deck slabs or other concrete components

**5.3.6** Available standards and codes of practice—There are a couple of existing standards available in the United States that pertain to the application of RH sensors. To prevent the delamination, or debonding, of certain floor coverings, internal RH criteria may be specified prior to coating or membrane application. ASTM F2170 has been developed to standardize the determination of the actual internal RH of a concrete floor slab. Another application is the determination of the actual moisture content at discrete points within a porous material—for example, cement and concrete. This is done by creating a correlation between the internal RH of a material and the corresponding moisture content, over a range of internal RH values and temperatures. A process by which one might create this correlation, or sorption isotherm, has been outlined by ASTM C1498.

## 5.4—Load cells

**5.4.1** *Physical basis and structural property inferred*—Load cells are sensors that convert weight or force into an

Table 5.3.4—Summary of strengths and limitations of humidity sensors

Description	Strengths	Limitations		
Resistive and capacitive resistive polymer sensors	<ul> <li>(a) Easy to deploy</li> <li>(b) Stable long-term</li> <li>(c) Resistive polymer sensors exhibit high linearity over broad measurement range</li> <li>(d) Inexpensive</li> </ul>	<ul> <li>(a) Each sensor requires its own wiring</li> <li>(b) Long-term exposure to extreme operating conditions might cause shift in response</li> <li>(c) Upper RH measurement limit</li> <li>(d) Measurement errors due to natural weathering and thermal cycling</li> </ul>		
FOS	<ul><li>(a) Allows for multiple measurement points along fiber</li><li>(b) Does not require wiring at each sensor location</li></ul>	(a) Expensive compared to other technologies		
	This is a preview. Click here to purc	hase the full publication		