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REVIEW

Temperature and humidity sensor technology for concrete health assessment: a review

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Abstract
The information of vital parameters within the concrete form the basis of maintenance, rehabilitation, repairing, upgradation or rebuilding of concrete structures. The information from the concrete helps in preempting further action or sequence of procedures, for long and sustainable service life. The objective of this review paper is to update and analyze the research that has been undertaken to capture and assess the thermal and humidity changes in concrete structure through sensors. The review while discussing the importance of structural health monitoring of concrete structures assesses the performances of the latest relevant sensor technology in vogue. Due to the environmental robustness, minimal size, quick response and high accuracy, major emphasis has been laid on the design of sensors based on fiber optic and Bragg grating. Both these technologies shall continue progress and generate more efficient and path breaking sensors in near future. Currently, the problems of relay, recalibration or replacement over a long period of time remain the big issues, in sensor technology and its advancement.

Keywords Temperature sensors · Humidity sensors · Structural health monitoring · Fiber optic sensors · Fiber Bragg grating sensors

Introduction

Concrete is the second most consumed material on the earth and the primary infrastructural bWuilding medium thus far. The timely monitoring, review and rehabilitation processes can hugely enhance the environmental and economic sustainability of concrete structures. For example, monitoring of humidity and pH levels in concrete sewer conduits and structure, or sulfate deposition through humidity in coastal structures are critical for its health, longevity and timely rehabilitation/repair processes. Likewise, the simultaneous exposure of extreme load and environmental conditions during the concrete service life can cause stress, cracking and deformation, which result in structural incompetence and failure [1]. The "cradle to grave" life cycle performance monitoring of concrete structure includes identification of critical performance criteria and determination of cause, type and extent of damage on the composite structure.

The adaptability to the emerging technologies like Bragg grating, fiber optics, electrochemical, wireless, self-sensing and piezoelectric technologies has boasted the structural health monitoring of concrete structures. Although the usage of sensors as a structural health monitoring tool is still in its primordial stages, its maximized utility and ultimate efficiency face major challenges. The objective of this review paper is to update and analyze the research that has been undertaken to capture and assess the thermal and humidity changes in concrete structure through sensors. The study assesses the suitability of different temperature and humidity sensor types, with respect to the sensor placement (surface or immediately surrounding, or within a concrete matrix) ambient conditions (environmental conditions), data transmission and service life. The review while discussing the importance of structural health monitoring of concrete structures assesses the performances as well as shortcomings of the temperature and humidity sensor technology in vogue.

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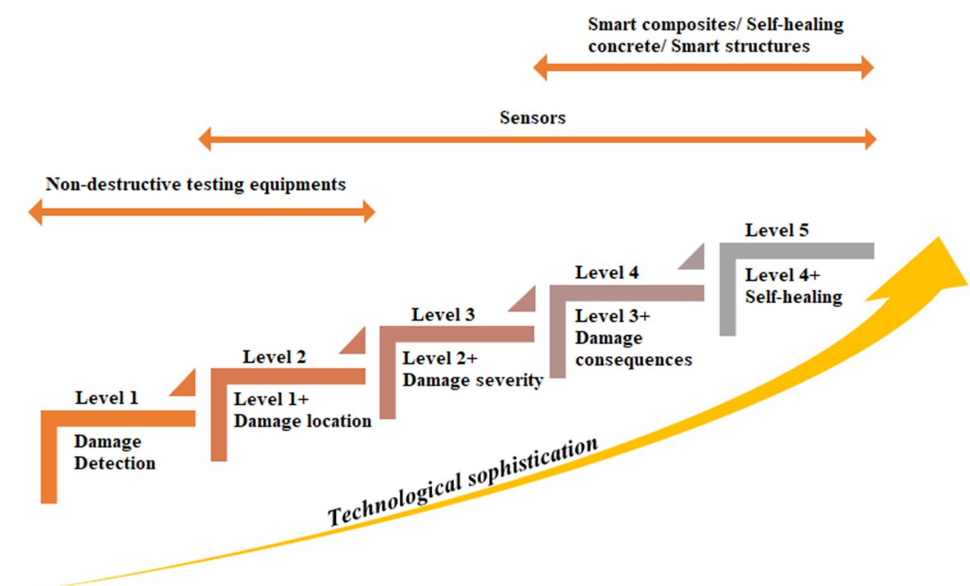
Structural health monitoring of concrete structures

In structural health monitoring (SHM) system, mapping, assessing and diagnosing of the concrete structural health form the core of monitoring system. Unlike the conventional, costly and cumbersome, method of manual evaluation of structural health at fixed time space, the modern intervention through sensor technology, artificial intelligence, wireless communication and data processing enable fast and accurate assessment/mapping of unforeseen structural degradation/failures with optimal costs, thereby enhancing longevity/service life. Latest permanent installations, capable of continuous and systematic diagnosis, can monitor cracks, pressure, weathering effects, chemical penetration, deformation, pH, humidity or temperature to assess the cause and severity of damage [1–3]. The measurement of either strain or temperature or both is main requirements for the assessment of these parameters.

Based on technical sophistication and working capabilities, SHM can be classified into five levels as shown in Fig. 1 [4, 5]. While the level 1 supports the detection of damage such as cracks or caving through NDTs, level 2, involving sensors, provides information regarding the damage location. The sensors can be mainly classified between levels 2 and 5, while as the smart composites, self-healing concrete and smart structures can be categorized in levels 4 and 5 [4, 6]. The smart composites, self-healing concrete and smart structures manifest their own functions based on the sensed environmental changes and damage assessment. Embedded or surface bonded concrete sensors of different types provide unprecedented continuous data to evaluate and track, and key structural parameters during its service life on real-time basis.

Figure 2 shows a typical concrete SHM system process flow that is based on key structural performance (KSP) parameter data collection, transmission, processing, visualization analysis and decision-making [4, 7]. KSP data are collected from embedded sensors such as service loads,

Fig. 1 SHM classification based on technical sophistication and working capabilities



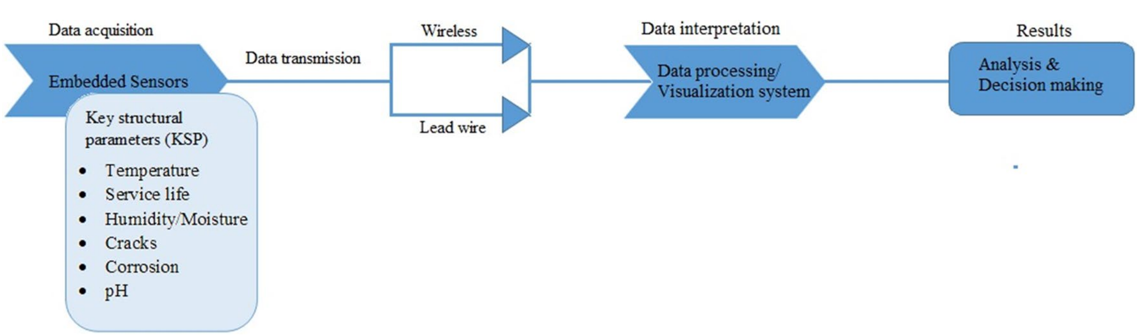


Fig. 2 Typical automated concrete SHM system process flow

cracks, corrosion rate, moisture, and pH. The embedded sensors collect the data in terms of temperature, humidity, service loads, pH, cracks, etc. and feed to data processing and visualization system through lead wire or a wireless system for visualization and data analysis by software system. The sensors in concrete (new as well as existing structure) are either embedded within the matrix or bonded to the member surface for real-time material assessment. Some of the limitations in embedded sensors is, limited service life, if it is battery operated, development of small cracks (< 1 mm) around the implanted sensors, sensor drift, because recalibration is difficult or impossible. Further, under mechanical loads and ambient changes like temperature or moisture, local stress concentration is induced by embedded sensors resulting in significant change in its response and sensor-composite interface de-bonding. The difference in thermoelasticity of the sensors and matrix also contributes to the severity of stress concentration. However, incorporation of embedded optical fibers smaller than 125 µm has shown negligible impact on strength and fatigue life of composite. The most common fabrication process adopted for laying optical fiber sensors is the expertise intensive hand layup and pre-preg layup methods [9]. Positioning of the optical sensor is highly application specific and depends on the location of the areas where parameters need to be monitored. Selection of sensors mainly depends on the KSP that needs to be assessed, robustness of sensor, duration and timescale of monitoring, structural condition and type [9, 10]. Based on the operational modes, sensors are mainly classified as resistance strain gauges, linear potentiometers, vibrating wire strain gauges, accelerometers, thermistors, corrosion monitoring sensors and fiber optic (SOFO) sensors [11, 12]. The use of physical monitoring principles, the sensors and the monitoring systems in condition monitoring to risk and asset management in SHM system depends on quality, cost efficiency and paybacks.

Sensor technology and design in vogue

Multiple sensor system and complex data processing techniques are required in complex SHM systems, especially in difficult-to-access structures, to monitor ambient conditions as well as undertake risk and asset management. Fiber-optic sensors are currently the most commonly used and evolving sensor technology, mainly based on structures, such as fiber Bragg grating (FBG) [13], tapered fiber [14], Fabry-P´erot interferometer (FPI) [15], AND Mach–Zehnder interferometer (MZI) [16]. The sensing function of optical fibers, mostly made out of glass and polymer optical fibers, is based on the changes in the light signals transmitted through it. A cylindrical core enclosed in a polymer- or metal-coated concentric cladding is capable of transmitting light through long distance, without amplification (Fig. 3a). The characteristics of an output signal or reflected wavelength are changed due to exposure of external perturbations or deformation during transmission. The main advantage of optical fiber sensors includes higher sensitivity, economic viability, minimal dimensions and weight/ minimal electromagnetic interference [17–20]. The fiber optic Bragg grating (FBG) is the most commonly used sensor, while as other main types of fiber optic sensors include interferometric, microbend, intensity, hybrid sensors, distributed polarimetric and wavelengths [21–23] (Fig. 3b). In FBG, the exposure of the core to an intense optical interference pattern gives rise to the periodic variation of the refractive index along the fiber length. The sensors withstand signal intensity fluctuations, due to the provision of spectrally encoded signal [24, 25].

Apart from uniform period, standard Bragg gratings having chirped gratings come with gradual period distribution, while the tilted fiber Bragg gratings (TFBG) have angular gratings for strain temperature. Within the composite material, the variation in the grating period provides standalone transmission between the spectrum wavelength and the gauge section position, which is a significant advantage of chirped FBG sensors over the conventional FBG sensors [26]. For acoustic emission (AE) measurement, phase-shifted FBG (PS-FBG) sensor with its interrogation system has proven to be highly sensitive, with extremely sharp resonance, wavelength multiplexer and also as a strain sensor that can map very small strain changes. Polymer FBGs on the other hand provide an advantage of higher-temperature sensitivity, larger strain range and the absence of buffer coating [8].

The three types of interferometric fiber sensors mainly used for strain/temperature measurements include extrinsic Fabry–Perot interferometers (EFPI), Sagnac fiber loop mirror (FLM) and microhole collapsed modal interferometers sensors. Fabry–Perot interferometer (FPI) generally consists of two parallel reflecting surfaces separated by a certain distance. The interference in an extrinsic FPI sensor occurs due to the multiple super-positions of both reflected and transmitted beams at two parallel surfaces. In fiber optic Sagnac interferometers (SIs), input light is split into two parts propagating in the opposite directions by a 3 dB fiber coupler and these two counter-propagating beams are combined again at the same coupler. Fiber optic microbend sensors are capable of measuring parameters such as acceleration, temperature, pressure, displacement and strain. Fiber optic microbend sensor is typically formed by passing the fiber between two sets of corrugations. Due to the mechanical wave touching optical fiber, coupling is created between propagating and radiation modes resulting in optical signal that can be related to stress waves released by delamination, matrix cracking or reinforcing fiber rupture [27, 28].

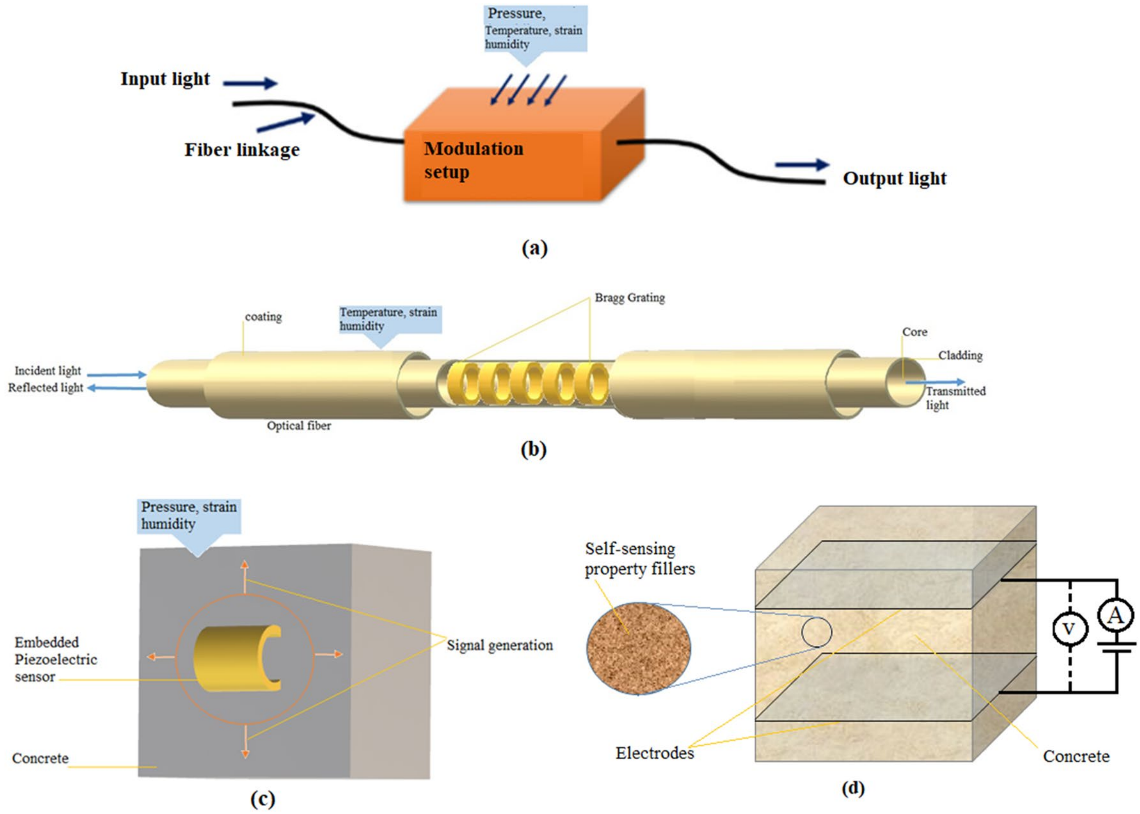


Fig. 3 Sensor samples (**a**) fiber Bragg grating sensor, (**b**) piezoelectric sensor and (**c**) self-sensing sensors

A piezoelectric sensor is capable of measuring parametric variation in pressure, temperature, acoustic emission, force, strain and acceleration, by converting it into measurable electrical charge (Fig. 3c). Piezoelectric materials used as sensors, accelerators, transducers and actuators can significantly help in assessing structural damages, crack propagation through passive acoustic emission (AE) techniques and piezoelectric sensors [29, 30]. The down side of piezoelectric sensors is the water solubility, influence of the temperature, gradual electromechanical degradation of transducer, and the bonding layer influence between a PZT patch and a concrete structure.

The self-sensing concrete is piezoelectric composites, incorporated with materials like semi-conductive or conductive nanoparticles, carbon nanotube (CNT) and carbon nanofibers (CNFs) that possess intrinsic sensing properties, simultaneously actuates and senses both (Fig. 3d). While the self-sensing polymer matrix composites (PMCs) are mostly made of carbon element, due to cost efficiency, carbon elements like carbon particle (CP)-reinforced polymers, carbon fiber-reinforced polymers (CFRPs) or aramidic/carbon or glass/carbon hybrid composites are very common [31, 32]. The self-sensing concrete working principle is based on piezo-resistivity and the differences in electrical resistivity volume of concrete induced by damage and deformation of concrete that results in changes in the electrical resistivity. The crack generation or propagation results in an increase in the electrical signal, while a decrease in the resistivity is due to concealment of cracks [33, 34]. Further research is required to optimize the poor sensing repeatability, sensing efficiency/ accuracy under complex stress conditions or extreme environmental conditions and the dispersion of functional fillers in the composite matrix.

In pavements and bridges, weigh-in-motion (WIM) system integrated with fiber-optic sensors is developed to replace piezoelectric sensors to map truck weights and wheel loads [35, 36]. Similarly, embedded fiber-optic sensors are used in reinforced concrete road infrastructure for corrosion detection, through spectroscopic analysis of light signals reflected from a corroding structural element [37]. For the assessment of in temperature, strain and deflection measurement of pavement quasi-distributed fiber-optic sensors using fiber Bragg grating (FBG) technology has been commonly used [38, 39]. A 3D embeddable strain sensor with three FBG strain sensors is embedded in fiber-reinforced polymer (FRP) and is used to monitor 3D strain of highway pavement. Composite structure sensor consisting of an F-P cavity formed by ultraviolet adhesive (NOA78) and a polymer fiber grating is used to detect temperature and humidity simultaneously [40].

Wireless sensors connection to piezoelectric, electrochemical or other types of sensors, through wireless nodes and platforms, enable seamless data acquisition. The wireless smart sensors are capable of measuring, filtering, sharing and analyzing readings from a large variety of sensors. The wireless sensor network motes comprise of a microcontroller, sensors, memory, a power unit and a communication module that gauge the environmental changes in the concrete and communicate it to the sink node through wireless links after performing collaborative signal processing [41, 42]. Radio frequency identification (RFID) and power-free wireless sensors are currently being researched to address the power consumption issues in wireless sensors [43–45]. RFID is wireless sensors based on the electromagnetic or electrostatic coupling in the radio frequency portion of the electromagnetic spectrum to assess the condition of a composite. RFID system comprises of an antenna, a transceiver and a transponder that uses radio waves to transmit signals that activate the tag and then receives back the waves from the antenna, where it is translated into data. RFID is operated under two categories, near field and far field. In the near field, frequencies ranging between 125 and 13.56 MHz are used, while as in far field, ultra-high frequencies and microwaves ranging around 800 MHz to GHz are used [46].

Temperature sensors

Long-term monitoring of temperature in concrete structures, and not restricted to curing stages, can enhance the service life and longevity of structure by restricting the accelerated deterioration caused by combined effect of temperature and the chloride/sulfate effect [47]. The enhanced corrosion or hydrogen sulfide development in sewage systems [48–50] and tensile cracks in mass concrete structures like dams, retaining walls, etc., are caused by inappropriate temperature prevalence in composite structures. Also the thermal fluctuation during curing process results in loss of structural integrity and durability due to microcrack proliferation causing thermal stress and drying shrinkage. The temperature gradients also promote diffusion of moisture and chemical vapor into the pervious concrete microstructure, which results in overall durability issues over a long period of time [51, 52]. The most common types of thermal sensors in use include, resistance temperature detector, infrared sensors, thermometers, negative temperature coefficient thermistors, silicon diodes, change-of-state sensors and semiconductor-based sensors [53, 54]. The corrosive environment and load duration [55–57] are primarily known to impact efficacy of sensors in concrete. The long-term contact of strong acidic as well as alkaline medium together with a high concentration of sulfate and chloride, due to the ion permeation, can reduce the electrical resistivity of concrete, thereby destabilizing its sensing properties [58]. Besides the annual temperature variation of 20 to 60 C, the high pH value in concrete, which lies between 12 and 14, causes high chemical degradation and therefore necessitates the protection of circuit board and the sensors in robust casings [59]. Notwithstanding the limitations of conditions in concrete, interference in data transmission and battery efficacy, the fiber Bragg grating (FBG) and fiber optic are the leading methods of measuring temperatures within concrete structures [60].

FBG sensors, intrinsically passive with no electrical power requirement, which are made from extremely fine fibers of glass-based silica, have excellent corrosion resistant property and very high temperature and humidity measurement accuracy under harsh gaseous acidic environment. Due to smaller size/volume and absolute measurement, the temperature measurement responses are very fast. A typical FBG temperature sensor comprises of two series connected FBGs along the fiber, one coated with polyimide to withstand moisture sensitivity and the other left uncoated for temperature measurement [61] (Fig. 4). Fernando et al. [62] investigated the use of a FBG sensor for temperature and strain measurement in a reinforced concrete beam within first 28 days after pouring and structural response after

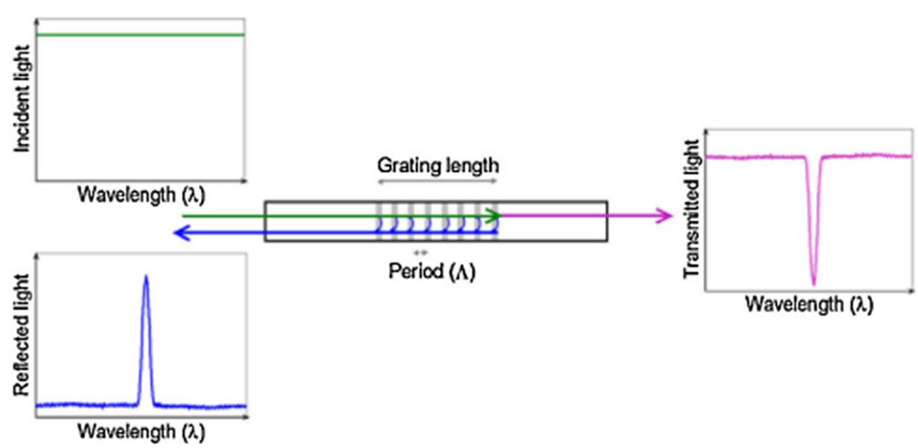


Fig. 4 Basic Bragg grating-based sensor system with transmissive/reflective detection options [63]

28 days curing period. A FBG sensor and a few thermocouples were embedded in the concrete beam at the casting stage. After curing, the beam was laterally loaded on a three-point bending arrangement until a crack formed on the beam and subsequently heated to 200 C with a 5 kN lateral load at mid-span. The FBG sensors undertook continuous real-time monitoring and data recording relating to temperatures, strains and vibrations. The monitoring damage was carried out with infrared red camera technique that recorded the propagation of a crack in a damaged structure. With the use of proper comparison technology, the structural health of concrete elements was accurately determined.

Górriz et al. [64] introduced a new regenerated FBG-based fiber optic sensor, capable of monitoring temperatures in concrete structures during fire accidents. A 5.8-m-long beam with 9 optical sensors in mid-span section was tested for 77 min. (@200 °C/min) ISO-834 fire curve under usual beam load. Comparison of results of new sensors electrical sensors and a numerical model showed a good fit, except in areas where concrete spalling caused distortions in the results and/or failure of the sensors. The study concluded FBG sensors as possible alternatives to electric sensors, in places such as power plants, or electrified railways where there is a limitation to the use of other sensor systems because of electromagnetic interference issues. Rinaudo et al. [63] fabricated fiber optic sensors, based on regenerated fiber Bragg gratings, for measuring high temperatures. Under ISO 834 fire curve conditions for one hour, at temperature increments of the order of 200 °C/min, sensors measured maximum gas temperatures of circa 970 °C showed good agreement with those provided by thermocouples in the same position. Barrera et al. [65] fabricated temperature sensors based on regenerated fiber Bragg gratings for measurements up to 1100. The optical fiber is protected with a ceramic tube which in turn is shielded with a thick metal casing, prior to the grating regeneration. The response and recovery times of packaged sensors were found to be, respectively, ~ 9 s and ~ 22 s. Habisreuther et al. [66] designed highly precise multimode single-crystalline sapphire inscribed fiber Bragg gratings inscribed for measurement of temperatures up to 1900 °C, which allowed signal processing with a temperature resolution better than ± 2 K. The main advantages include signal multiplexing, large temperature bandwidth and insensitivity to electromagnetic fields.

Brillouin scattering-based distributed fiber optic sensor has been used to measure temperature distributions and detect cracks in concrete structures subjected to fire. Concrete cracking did not affect the sensitivity of the distributed sensor but concrete spalling broke the optical fiber loop required for PPP-BOTDA measurements [67]. Similarly, Brillouin scattering-based fiber optic sensor used for measurement of temperature and building code recommended material parameters. The results of temperature sensor when compared with thermocouple measurements showed less than 4.7% average difference at 95% confidence level [68]. Peng et al. [69] developed positioning method of temperature sensors, based on the natural neighbor interpolation algorithm, and the cross-validation, to determine the placement of temperature sensors in a concrete dam. In a super-high arch dam, the optimal arrangement of thermometers, distributed optical fibers and infrared thermal imagers are undertaken for real-time measurement of concrete temperature. The dam global thermal field results were obtained with reasonable accuracy. The restructured thermal field is consistent with the actual situation of the super-high arch dam.

Comparison with commercially available thermo-couples showed that the surface acoustic wave (SAW) temperature sensor system was successful in detecting temperature over a wide range in all tested conditions with a high degree of accuracy and short interrogation time [70]. Nanotechnology/microelectromechanical systems (MEMS)-based microcantilever beams and expandable water vapor-sensitive nanopolymer film have been used to measure temperature and internal relative humidity. The MEMS was found to survive both the concrete corrosive environment and internal and external stresses and was able to measure moisture content and temperature effectively and with a high sensitivity. However, relevant issues like long-term behavior and repeatable use of MEMS, wireless integration like signal processing, communication, data storage, etc. needed further investigation [42].

Chen et al. [71] introduced microstrip antenna-enabled embedded passive wireless sensor based on radio frequency identification (RFID) technology. The wireless sensor consisted of an energy management section, a digital section and an RFID section. Despite the high losses of concrete, the on-site testing laboratory test results showed that the sensor tag provided reliable communication performance in passive mode. Compared to the results of thermocouple, the results of sensor were highly consistent, with maximum reader-tag communication distance was 7 m at 915 MHz. Chen et al. [72] designed long-range application, passive wireless temperature sensor based on backscattering mechanism of RFID technology for ultra-low power application. The temperature-digital conversion in frequency domain in sensor is achieved due to phase-locked loop-based architecture. The power conversion efficiency is improved due to gate-boosting rectifier. A high linearity with a resolution of 0.3 °C/LSB is achieved. The minimum power dissipation measured was 2.7 μW, with a maximum operating distance of 34 m under 4 W radiation power (Fig. 5). Deng et al. [73] designed a ultra-low embedded power temperature sensor for passive RFID tags, wherein the temperature variation, phase-locked loop (PLL)-based sensor interface, is converted into to a PTAT current and subsequently relayed into a temperature-controlled frequency, without an external reference clock.

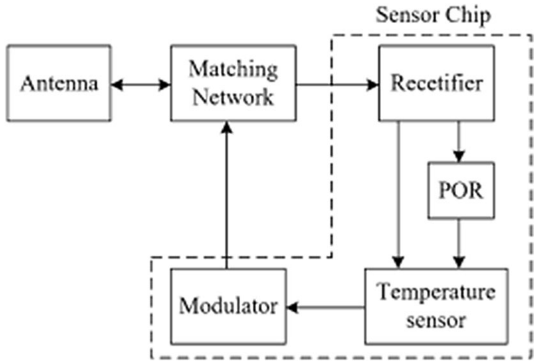


Fig. 5 Wireless sensor architecture

The setup, with the aid of TSMC 0.18 1P6M mixed-signal CMOS process, occupied an area of 0.021 mm2. Measurement results of the embedded sensor within the tag system show a 92 nW power dissipation under 1.0 V supply voltage at room temperature, with a sensing resolution of 0.15 °C/LSB and a sensing accuracy of − 0.7/0.6 °C from − 30 to 70 °C after 1-point calibration at 30 °C.

Liu et al. [74] introduced the passive radio frequency identification (RFID) sensor tag embedded for concrete temperature monitoring with a T-type antenna to reduce the influences of concrete electromagnetic parameters during the drying process. The ultra-high-frequency RFID sensor tag with communication protocol operates in passive mode, which converted the sensor signals to corresponding digital signals without an external reference clock due to the adoption of phase-locked loop setup. The tested results show high consistency with the results tested by a thermocouple, with the maximum communicating distance of 7 m between reader and tag at the operating frequency of 915 MHz. Federico and Ceminari [75] designed a novel time-domain temperature sensor architecture with all the implied signals generated within the sensor only temperature dependent. The design is autonomous and more predictable as it negates the sensor efficiency dependence on the external signal stability. The sensor was implemented in a 130-nm technology and integrated in the same chip with a RFID Tag, which activates the sensor operation when it receives one of the EPCGen 2 user reserved command.

Humidity sensors

The environmental conditions of composite structures are not defined solely by temperature data alone, but the presence of water and moisture also has predominant effect on corrosion, carbonation, electrical resistance or alkali-silica reaction, etc. Different humidity sensors, varying in operational mechanism, technological setup and hygroscopic sensing material like electrolytes, ceramics, etc., are available commercially. In terms of operational mechanism, like temperature sensors, the humidity sensors are based on resistive, capacitive, mechanical/electrical resonant devices. Previously, the discrete resistive or capacitive sensing element was interfaced with microcontroller unit through external circuit, with porous silicon/ceramics and electrolytes used as humidity sensing materials [76, 77]. Currently, FBG and fiber optic sensors, being small and compatible under harsh conditions, has the advantage of linear response to humidity and is easy to multiplex. Generally, absorption/scattering of the evanescent tail [78, 79] and the swelling of the hygroscopic materials [80, 81] in response to the humidity are the two primary working principles of fiber optic sensors. The applications of plastic optical fibers with the use of conjugated green emitter [82], signal strength analysis of RFID tags [83], single tin oxide (SnO2) nanowire [84], silicon substrate with ZnO nanorod/ nanowire films [85], surface-modified piezoelectric crystal, nitrated polystyrene/ ultrathin LTA-zeolite film-based piezoelectric devices [86] are some of the techniques that are currently used in measurement of humidity within the composite.

FBGs are also connected with hollow-core fiber coated with a composite film of carboxymethyl cellulose (CMC)/ carbon nanotubes (CNTs) for high sensitivity and fast response of simultaneous measurement of humidity and temperature. The results showed that the humidity sensitivity of the sensor with CMC film was 170.55 pm/%RH, while the sensitivity of the sensor with CMC/CNTs composite film was 230.95 pm/%RH. The humidity-insensitive FBG can be used to obtain accurate temperature information, and the temperature sensitivity is 26.35 pm/ °C. The study not only proved that CMC is an excellent humidity sensitive material for optical fiber sensors but also showed that carbon nanotubes can increase the humidity sensitivity of the hydrogel film effectively [87]. Similarly, studies have shown that the optical fiber temperature and humidity sensor composed of a polymethyl methacrylate (PMMA) microsphere and a FBG are capable of monitoring the environment temperature and humidity, simultaneously (Fig. 6). The response sensitivity of the Fabry-P´erot (F–P), between PMMA microsphere and the fiber end face, is about 127 pm/%RH, for relative humidity change from 35 to 85%. For temperature changes from 33 °C to 58 °C, the response sensitivity of the F–P and FBG was about 45.68 pm/ °C and 10 pm/ °C, respectively. When temperature and humidity changed simultaneously, these two parameters could be monitored simultaneously by using the dual-parameter measurement matrix method. The optical fiber dual-parameter sensor offered numerous advantages, such as low cost, high sensitivity and easy fabrication [88].

Su et al. [89] reported measuring range of 7%RH to 91.2%RH and the sensitivity is about 0.07 nm/(1%) for fiber Fabry–Perot interferometer coated with PVA film

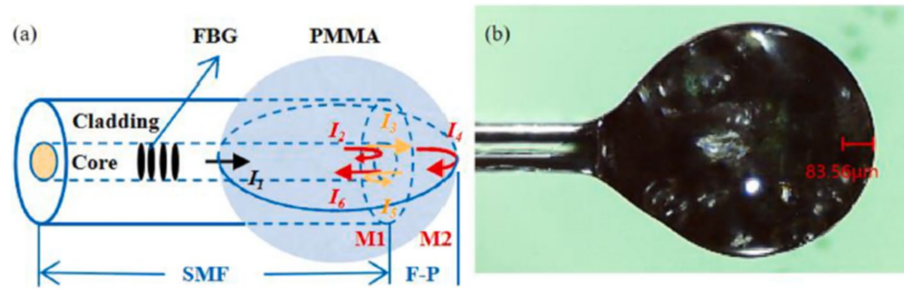


Fig. 6 **a** Sensor structure and **b** micrograph of sensor prepared xperimentally [65]

on the ending face of a single-mode fiber (SMF) to form a Fabry–Perot cavity with free spectra range (FSR) of 15 nm. The sensor provided good environment monitoring application at lower cost with compact size and simple fabrication. Zhao et al. [90] used graphene quantum dots (GQDs) and PVA, filled into the hollow core fiber, spliced at the end of a single-mode fiber in optic fiber Fabry–Perot interferometer for relative humidity sensing and experimentally demonstrated. With the increase in humidity, the refractive index of graphene quantum dots (GQDs) and PVA compounds decreases and the length of the Fabry–Perot cavity elongates, thereby characterizing the variation in humidity values. Results revealed that the wavelength shift shows good linearity with the humidity changing from 13.47%RH to 81.34%RH, and the sensitivity is 117.25 pm/%RH with the linearity relevancy of 0.9983. Oliveira et al. [40] reported developed of an efficient, a dual-fiber sensor, capable of measuring both humidity and temperature, with a combination of adhesive based Fabry–Pérot cavity (NOA78) and a polymer fiber Bragg grating. A modified version of the self-written waveguide technology was used to fabricate Fabry–Pérot structure, while as the flat sides microstructured polymer fiber (mPOF) using the phase mask technology through the 248-nm UV laser was used for polymer fiber Bragg grating.

Li et al. [91] developed highly sensitive, ultra-longer fiber cantilever taper for simultaneous measurement of the temperature and relative humidity by heating a SMF with arc discharge method. An ultra-longer fiber cantilever taper for simultaneous measurement of the temperature and relative humidity (RH) with high sensitivities was proposed. The fabrication of structure included fiber cleaving, splicing and tapering, with cantilever taper length of approximately 1.5 mm. The humidity sensitivity was –31.2 pm/% RH and –29.2 pm/% RH with a broad humidity interval ranging from 20% RH to 70% RH. Dong et al. [92] structured an optical fiber sensor coated with hydroxyethyl cellulose (HEC) hydrogel by splicing SMF, multi-mode fiber (MMF), dispersion compensation fiber (DCF), MMF and SMF, for measurement of temperature and humidity. The design eliminated the cross-sensitivity of temperature and humidity in senor by using two-parameter measurement matrix method and monitoring the shift of resonant spectrum dips. Compared to complex humidity-sensitive material coating and microstructure fabrication which are very costly and complex in design, the polymer optical fiber is cheap and simple.

The commonly used humidity sensitive materials in optical fiber humidity sensors include hydrogel [93], nanomaterial [94], metal [95], etc. Asiah et al. [96] fabricated a simple humidity sensor using a tapered fiber with a moisture sensitive hydrogel coating hydroxyethyl cellulose/polyvinylidene fluoride polymers. The refractive index of the fiber coating is altered due to the changes in humidity level thereby leading to variation in optical output power. The refractive index of hydrogel coating decreases with the rise in humidity that allows more light to be transmitted in humid state. With a change in humidity from 50 to 80%, a difference of up to 0.89 dB of the transmitted optical power is observed. The sensor showed a sensitivity of about 0.0228 dB/%RH with a slope linearity of more than 99.91%. Yan et al. [97] designed a high-performance PVA-coated optical fiber sensor with knob-integrated fiber Bragg grating for simultaneous measurement of humidity and temperature. The knob-shaped taper not only excited the cladding modes, but also recoupled the cladding modes back into the leading single-mode fiber. Results showed better humidity sensitivity of up to 1.2 dB/%RH within an RH range of 30–95% and the temperature sensitivity of 8.2 pm/ °C for temperature range of 25–60 °C.

The commercialized brands currently available for measuring and monitoring temperature and humidity include SmartRock [98], TEMPCON [99], and CONCRETE SENSORS [100] which are mostly attached to the rebar before the concrete pour, and their function is to assess the temperature changes within the concrete structure through the project completion process (Table 1). The use of radio frequency integrated circuit (RFIC) transmitter [101], alkaline-resistant SHT15/SHT21S sensors [102], nanotechnology and microelectromechanical systems-based sensors (MEMS) [42], Fabry–Perot (FP) fiber optic sensor [103], etc. is the latest technologies used to increase the efficiency and longevity of temperature sensors. The use of thermography technology to monitor a cracked structure enables monitoring of crack propagation in a structure that is exposed

Table 1 Commercialized brands currently available for measuring and monitoring concrete

Device	Manufacturer	Device setup	Remarks
Command Center	Transtec Group	Wire sensors with wireless nodes with or without hub	Concrete temperature and maturity monitoring. Wired or wireless data transmission through Bluetooth
Concremote	Doka	Wire sensors with wireless nodes with or without hub	Concrete temperature and maturity monitoring. Both concrete surface and embed type. Data record and transmission directly to cloud through cell network
Concrete Sensors	Structural Health Systems Inc	Fully embedded wireless sensors with or without hub	Concrete temperature and humidity monitoring. Data retrieval and analysis through mobile application via Bluetooth. Another variant directly connects to a local gateway for data transmission to the cloud
Con-Cure NEX	Nex Monitoring System	Wired loggers/wire sensors with wireless nodes with or without hub	Wired maturity loggers are embedded in the concrete with wire connected either to a hand-held device to download the data, or to a wireless node that then transmits data to the cloud through cell network or save it on an SD card
Converge	Converge Technology	Wire sensors with wireless nodes with or without hub/fully embedded wireless sensors with or without hub	Concrete temperature and maturity monitoring. Wired sensors connected to wireless nodes for transmission to the cloud. In fully wireless sensors, data are to either a mobile device or a local hub and then to the cloud through cell network
Exact sensors	Exact technology	Wire sensors with wireless nodes with or without hub	Concrete strength and maturity monitoring. The wire lead is then connected to a wireless node that sends the data to a local hub for transmission to the cloud through the cell network
HardTrack	Wake Inc	Wire sensors with wireless nodes with or without hub/fully embedded wireless sensors with or without hub	Concrete temperature and maturity monitoring. Temperature measurement cable is connected to an RFID reader. The RFID tag can either be embedded in the concrete or placed outside to be reused. Users can use an RFID reader to retrieve the recorded data or install a local hub to wirelessly download the data for transmission to the cloud
intelliRock	Engius (Flir)	Wired loggers	The wired maturity loggers are placed inside the concrete with wire connected to a hand-held device to download and analyze the data, or it can be connected to a wireless transmitter to send the data to the cloud
Lumicon concrete sensor	AOMS Technologies	Fully embedded wireless sensors with or without hub	Concrete temperature, humidity and maturity monitoring. Temperature measurement at multiple locations across its cable. The cable end connected to a wireless transmitter that then sends data to a local hub and then to the cloud. The data analysis and concrete maturity calculations are performed on the cloud. Data are also accessible using mobile app
Maturix sensors	Sensohive	Thermocouple sensors	Concrete temperature and maturity monitoring. With thermocouple sensors, one end of the thermocouple wires is embedded in the concrete and the other end needs to be connected to a node. The nodes record the concrete temperature data and send it wirelessly to the cloud

Table 1 (continued)

Device	Manufacturer	Device setup	Remarks
Tempcon	Tempcon Instrumentation	Wire sensors with wireless nodes with or without hub /fully embedded wireless sensors with or without hub	Concrete high-temperature monitoring. Temperature probes and sensors, including thermocouple sensors, RTD sensors, and thermistor sensors. Can measure temperatures up to 600 °C
SmartRock	Giatec	Fully embedded wireless sensors with or without hub	The recorded data sent using Bluetooth either to a mobile device or to a SmartHub, which transmits the data to the cloud through cell network. Giatec also offers SmartRock Plus sensors exclusively through concrete producers that are pre-calibrated to their concrete mixes
vOrb	Quadrel	Fully embedded wireless sensors with or without hub	Concrete temperature and maturity monitoring. The vOrb sensors which use Wi-Fi communication protocol are embedded in the concrete. The data need to be retrieved via a local hub before they are transmitted to the cloud

to high temperatures as seen in a nuclear plant, etc. The thermography sensors are based on the relationship between thermal radiation and temperature, wherein the heteromorphic structure of the material is represented by the variation in surface temperature distribution, which aids in detection of defects and its location. The use of such technology could improve safety by early identification of structural flaws that may have otherwise been overlooked [104].

Conclusion

Currently enormous efforts have been directed to investigate and design automated systems for the continuous monitoring of temperature and humidity in the concrete structures. The major emphasis has been on the design of sensors based on fiber optic, Bragg grating due to their environmental robustness, minimal size, quick response and high accuracy. Both these technologies shall continue progress and generate more efficient and path breaking sensors in near future. Durability of sensor hardware and inter-effect of different conditions remains the biggest challenge especially in embedded sensors. The technological issues like the protection of electronics, recalibration or replacement, seamless relay of wireless signals through the concrete, over a long period of time and distribution of sensors are some of the major hurdles. However, last decade has witnessed more standardization and sophistication in hardware component design. Some of the recent improvements include the advancement in durability and the predictive performance of the concrete based on captured data.

With the advancement in electronics, machine learning and artificial intelligence and minimal energy requirement in wireless technology, high-end analysis will be better at generating new insight on detecting defects, detecting patterns and training algorithms to understand concrete behavior under different conditions, environments and mix designs. With the advancement in electronics, machine learning and artificial intelligence and minimal energy requirement in wireless technology, high-end analysis will be better at generating new insight on detecting defects, detecting patterns and training algorithms to understand concrete behavior under different conditions, environments and mix designs. Simulation of environmental (jobsite) conditions in laboratories will enhance accuracy in test results and predictive analysis. Last but not the least, the efficient use of sensors and collected data shall provide an opportunity for addition carbon saving through optimized material and process management.

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reviewing and editing. MIA contributed to reviewing and editing. Prof. RD contributed to reviewing and editing.

Data availability Relevant data will be made available upon request.

Declarations

Conflict of interest This is to certify that the authors of the above listed paper have no conflict of interest. The authors declare that they have no competing interest and the work is original.

Ethical approval Ethics approval was not required for this review manuscript.

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