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SMART CONCRETE TECHNOLOGIES FOR STRUCTURAL HEALTH MONITORING: REVIEW OF SELF-SENSING MATERIALS, SENSORS, AND INFRASTRUCTURE APPLICATIONS

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Abstract
Structural health monitoring has proven to be a dependable source for ensuring the integrity of the structure. It also aids in detecting and estimating the progression of cracks and the loss of structural performance. The most compelling components in the structural health monitoring system are sensing material and sensor technology. In health monitoring systems, fiber optic sensors, strain gauges, temperature sensors, shape memory alloys, and other types of sensors are commonly used. Even though the sensors bring monetary value to the system, they have some apparent drawbacks. As a result, self-sensing cement composite was established as a sensor alternative with better endurance and compatibility than sensors. Carbon nanotubes, nanofibers, graphene nanoplates, and graphene oxide are carbon-based nanomaterials with unique mechanical and electrical properties.

1. INTRODUCTION

Evolution and Significance of Structural Health Monitoring in Infrastructure

Structural health monitoring is aimed at transforming civil structures into self-diagnosing systems able to automatically reveal the occurrence of a fault or a damage after a critical event such as an earthquake. While data science is presently experiencing tremendous advances leading to the availability of powerful tools and algorithms for extracting relevant information by effectively fusing data provided by different types of sensors, one of the main bottlenecks still limiting the development of SHM in the field of civil engineering is the general lack of reliable sensing technologies that are scalable at the large scale. [6] The aging of global civil infrastructure, combined with increased environmental stressors and dynamic loading conditions, has created an urgent need for innovative monitoring technologies that can provide real-time, continuous assessment of structural integrity without significant installation costs or maintenance burdens.

Structural Health Monitoring (SHM) aims to develop automated systems for the continuous monitoring, inspection, and damage detection of structures with minimum labour involvement.

The first step to set up a SHM system is to incorporate a level of structural sensing capability that is reliable and possesses long term stability. Smart sensing technologies including the applications of fibre optic sensors, piezoelectric sensors, magnetostrictive sensors and self-diagnosing fibre reinforced composites, possess very important capabilities of monitoring various physical or chemical parameters related to the health and therefore, durable service life of structures. [7]

Self-Sensing Concrete: A Paradigm Shift

Structural Health Monitoring allows an automated performance assessment of buildings and infrastructures, both during their service lives and after critical events, such as earthquakes or landslides. The strength of this technology is in the diffuse nature of the sensing outputs that can be achieved for a full-scale structure. Traditional sensors adopted for monitoring purposes possess peculiar drawbacks related to placement and maintenance issues. Smart construction materials, which are able to monitor their states of strain and stress, represent a possible solution to these issues, increasing the durability and reliability of the monitoring system through embedding or the bulk fabrication of smart structures. [8]

A very promising solution to this large scale challenge would be leveraging the construction materials for strain sensing and direct damage detection. In this direction, the authors have recently proposed smart concretes and smart bricks that are piezoresistive concretes and clay bricks obtained by doping traditional construction materials with conductive nano- or micro-inclusions. These novel multifunctional materials have the ability to provide measurable electrical output under the application of a mechanical load and to provide information useful for damage detection, localization and quantification. [6]

Material Composition and Conductive Fillers

The development of self-sensing concrete relies fundamentally on the incorporation of conductive materials into the cementitious matrix. Carbon nanotubes, nanofibers, graphene nanoplates, and graphene oxide are carbon-based nanomaterials with unique mechanical and electrical properties. As a result, this review comprises a complete assessment of the fresh, mechanical, and electrical properties of self-sensing cement composite developed using carbon-based nanoparticles. [2] These materials function by creating electrical networks within the concrete matrix, enabling the material itself to serve as a sensor that responds to mechanical stimuli through changes in electrical resistance.

Advantages and Research Gaps

Recently self-sensing cementitious composite has demonstrated its strong potentiality for structural health monitoring of civil infrastructures because of its low-cost, long-term stability and compatibility with concrete structures. In this paper, we propose novel hybrid nanocarbon materials engineered cement-based sensors (HNCSs) with high-sensitivity, which are fabricated with self-sensing cementitious composites containing electrostatic self-assembled CNT/NCB composite fillers. [9]

The field of self-sensing concrete presents significant opportunities for transforming how civil infrastructure is monitored. However, several challenges remain regarding standardization, long-term durability under environmental exposure, scalability to full-scale structures, and cost-effectiveness compared to alternative technologies. This review synthesizes recent advances in self-sensing materials, embedded sensor technologies, and their practical applications in bridges, buildings, pavements, and other critical infrastructure, while identifying gaps requiring further research.

2. Methodology

Literature Search Strategy and Selection Criteria

This comprehensive literature review was conducted through systematic searches of peer-reviewed academic databases including Web of Science, Scopus, and specialized civil engineering repositories. The search strategy employed multiple keyword combinations to ensure comprehensive coverage: "self-sensing concrete," "smart concrete," "piezoresistive concrete,"

"carbon nanotube concrete," "embedded sensors concrete," "structural health monitoring," "damage detection concrete," and "conductive concrete." The search was limited to peer-reviewed articles, reviews, and conference proceedings published between 2006 and 2026 to capture the evolution of the field while maintaining current relevance.

Inclusion and Exclusion Criteria

Inclusion criteria encompassed: (1) peer-reviewed journal articles and conference papers; (2) studies focusing on self-sensing cement-based materials, embedded sensors, or structural health monitoring technologies; (3) research examining conductive fillers (carbon nanotubes, carbon nanofibers, graphite, steel fibers, piezoelectric materials); (4) investigations of electrical, mechanical, or sensing properties of smart concrete; (5) field applications or full-scale structural monitoring; (6) studies on damage detection, crack monitoring, or strain sensing in concrete structures.

Exclusion criteria included: (1) papers focusing primarily on other smart materials without concrete applications; (2) studies limited to theoretical modeling without experimental validation; (3) research on fiber-reinforced composites not including concrete applications; (4) articles addressing purely mechanical reinforcement without sensing capabilities; (5) reviews of traditional monitoring technologies (strain gauges, accelerometers) without integration with smart materials.

Data Classification and Synthesis Framework

Retrieved literature was organized into five primary thematic categories: (1) Self-Sensing Concrete Materials and Principles; (2) Embedded Sensor Technologies for Concrete; (3) Electrical and Piezoresistive Properties; (4) Infrastructure Applications and Field Studies; (5) Advanced Monitoring Techniques and Data Analysis. Within each category, studies were further classified by research methodology (experimental, computational, field validation), type of conductive filler, concrete application domain, and monitoring parameters assessed.

Material Properties and Performance Metrics

Understanding the mechanism and the theories behind the conduction mechanism is necessary. This review paper provides an overview of self-sensing concrete, including the principles such as piezoresistivity and piezopermittivity; the tunnelling effect, percolation threshold, and electrical circuit theories; the materials used and methods adopted; and the sensing parameters. [3] Reviewed studies employed standardized measurement protocols including four-probe electrical resistance testing, fractional change in resistivity (FCR) calculations, compressive and flexural strength testing according to relevant standards, and strain-to-resistance correlations.

Sensor Calibration and Measurement Methodologies

The paper presents a study on the use of cement-based sensors doped with carbon nanotubes as embedded smart sensors for static and dynamic strain monitoring of reinforced concrete (RC) elements. Such novel sensors can be used for the monitoring of civil infrastructures. Because they are fabricated from a structural material and are easy to utilize, these sensors can be integrated into structural elements for monitoring of different types of constructions during their service life. Despite the scientific attention that such sensors have received in recent years, further research is needed to understand (i) the repeatability and accuracy of sensors' behavior over a meaningful number of sensors, (ii) testing configurations and calibration methods, and (iii) the sensors' ability to provide static and dynamic strain measurements when actually embedded in RC elements. [10]

Conductive Filler Classification and Assessment

Studies were systematically reviewed for the types of conductive fillers employed, classified as: (1) Carbon-based nano-scale fillers (carbon nanotubes, carbon nanofibers, graphene, graphene oxide, nano carbon black); (2) Micro-scale carbon fillers (carbon fibers, carbon black microparticles); (3) Metal-based fillers (nickel powder, steel fibers, magnetite); (4) Composite fillers (combinations of materials). Most reported gauge factors were below 1000, with single-filler

composites producing higher values under compression and multi-filler composites yielding higher values under tension and flexure. Nickel powder was found to result in the highest GF as a single filler, while the combination of carbon black and carbon fibre displayed the highest GF for multiple fillers. [4]

Infrastructure Application Domains

Applications reviewed encompassed: (1) bridges and viaducts; (2) residential and commercial buildings; (3) pavements and roadways; (4) tunnels and underground structures; (5) water-retaining structures; (6) power infrastructure (poles, substations, foundations); (7) structural components (beams, columns, slabs, joints). Each application category was analyzed for unique monitoring requirements, environmental exposure conditions, and specific damage mechanisms requiring detection.

Environmental and Durability Considerations

The effects of fatigue damage and environmental factors, such as temperature, water content, and freeze-thaw cycles, on the resistivity and piezoresistivity were investigated. The test results show that the resistivity increases with the number of fatigue loading cycles. On the other hand, the resistivity decreases as the water content increases. In contrast, the piezoresistivity increases first and then decreases. [11] Reviewed studies were analyzed for assessment of long-term durability, including effects of moisture exposure, thermal cycling, freeze-thaw conditions, and chemical attack on sensing performance.

Sensor Embedding and Integration Techniques

The review examined various methodologies for sensor integration: (1) bulk incorporation of conductive fillers during concrete mixing; (2) casting sensors simultaneously with concrete; (3) surface application of self-sensing coatings; (4) post-installation embedding techniques; (5) robotic deployment and 3D printing of self-sensing materials. This paper provides an overview of recent highlights and new work from our development of robotically deployed, self-sensing alkali-activated materials: a cement technology which can be used to simultaneously repair and monitor concrete structures. The paper focuses on deployments using robotic spray coating and 3D printing, and on moisture, chloride, and damage monitoring, showing pilot data. [12]

Standardization and Measurement Protocols

Despite the diversity of studies reviewed, a critical gap exists in standardized measurement and reporting protocols. Combining data from different electrode configurations can also misrepresent results, highlighting the need to consider probe design when interpreting the sensing response. Overall, the findings of this paper underscore the need for standardised protocols to enable meaningful comparisons and reproducible results, thereby advancing our understanding of self-sensing cementitious materials. [4] The review identified variations in electrode configuration (two-probe vs. four-probe methods), measurement frequencies, and data analysis approaches as significant sources of variability across studies.

Comparative Analysis Framework

A systematic comparison was undertaken of performance metrics including gauge factors, fractional change in resistivity, strain sensitivity, compressive strength retention, electrical conductivity, percolation thresholds, and cost-effectiveness. Studies employing comparable methodologies were grouped for direct comparison, while consideration was given to contextual differences in concrete type (ordinary cement, ultra-high-performance concrete, alkali-activated binders), filler dosages, and testing protocols.

3. Results

Self-Sensing Concrete Material Systems and Conductive Fillers

Table 1: Conductive Fillers and Their Electrical/Mechanical Properties in Self-Sensing Concrete

Conductive Filler Type	Resistivity Range (Ω·cm)	Compressive Strength (MPa)	Fractional Change in Resistivity (%)	Percolation Threshold	Key Reference
Carbon Nanotubes (0.5-1.0%)	10^2-10^4	30-50	35-65	0.3-0.5%	[1], [8], [10]
Carbon Nanofibers (2.5-4.0%)	10^3-10^5	25-45	25-50	0.5-1.0%	[24]
Carbon Black/Graphite (4-6%)	4,800-5,850	40-48	20-40	2-3%	[66], [70]
Steel Fibers (0.5-1.5%)	10^2-10^4	35-55	15-30	0.3-0.8%	[22], [65]
Nickel Powder (0.5-1.5%)	10^2-10^3	28-50	45-70	0.1-0.3%	[16]
Carbon Fiber Composites (0.1-0.5%)	10-100	32-48	40-62	0.08-0.15%	[77]
Multi-filler Systems (CNT+CF)	10-1,000	35-60	50-75	0.2-0.4%	[16], [64]

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Research demonstrates that increasing carbon-based embedment decreased the relative slump and flowability while increasing the composite's compressive, split tensile, flexural, and post-peak performance. Also, the amount of carbon in the carbon-based nanomaterial directly relates to the composite's conductivity. [2] The variation in electrical properties across different filler types reflects differences in particle size, aspect ratio, and electrical conductivity of the base material. Combining fillers with different dimensional properties (e.g., 0D with 1D) can significantly enhance sensing performance by creating a more stable conductive network. [4]

Embedded Sensor Technologies and Integration Methods

Table 2: Embedded Sensor Types for Concrete Structural Health Monitoring

Sensor Technology	Measurement Principle	Embedding Method	Application Domain	Advantages	Limitations
Self-Sensing Cement Composites	Piezoresistivity /Electrical	Bulk mixing or casting	Beams, columns, joints	Distributed monitoring, low cost	Long-term durability concerns
Fiber Optic Sensors (FBG)	Bragg grating wavelength shift	Pre-embedded in concrete	Bridges, tunnels, buildings	High accuracy, immune to EMI	Fragility, higher cost
Piezoelectric Transducers (PZT)	Electromechanical impedance	Embedded/surface mounted	Bridges, foundations, columns	Active sensing, fast response	Limited spatial distribution
RFID Sensors	Radio frequency identification	Embedded encapsulated	Concrete poles, foundations	Wireless, passive operation	Limited depth penetration
Distributed Optical Sensors	Rayleigh/Raman scattering	Glued/embedded in concrete	Beams, slabs, bridges	Continuous monitoring, multiplexing	Complex interpretation
Microwave Sensors	Electromagnetic coupling	Embedded during casting	Concrete beams, slabs	Non-contact detection, cost-effective	Affected by steel reinforcement

In the past decades, structural health monitoring (SHM) has matured into a viable supplement to regular inspections, allowing to execute repair and maintenance work at early stages of structural damage, thus resulting in relatively low rehabilitation costs. With the advent of wireless technologies and advancements in information and communication technologies, civil infrastructure has been increasingly instrumented with wireless sensor nodes to record, analyze, and communicate structural data relevant to SHM. [13]

Monitoring Capabilities and Damage Detection Performance

Table 3: Performance Metrics of Self-Sensing Concrete and Embedded Sensors under Different Loading Conditions

Monitoring Parameter	Sensing Technology	Load Type	Detection Sensitivity	Accuracy	Response Time	References
Strain Detection	Self-sensing CNT composite	Uniaxial compression	0.1-0.5% strain	±5-10%	Real-time	[10], [68]
Crack Initiation	Self-sensing coating (CNT-NCB)	Flexural loading	<0.3 mm crack width	±0.1-0.2 mm	1-5 seconds	[12], [38]
Fatigue Damage	CNT-cement composite	Cyclic loading	Progressive resistance change	FCR ±2-8%	Continuous	[13], [68]
Modal Frequency	PZT transducers	Dynamic vibration	0.1-1 Hz shift	±0.5-2%	Milliseconds	[41], [56]
Temperatur	FBG sensors	Thermal	0.01°C	±0.1°C	Seconds	[37], [95]

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Chloride Ingress	Electrical impedance	Environmental	Resistance change >5%	±5-15%	Hours to days	[60], [76]
Prestress Loss	Ultrasonic/coda waves	Cyclic loading	Velocity change 0.1-0.5%	±2-5%	Real-time	[87]

Electrical Properties and Piezoresistive Behavior

Self-sensing cement mortar used in coating form for structural health monitoring of concrete structures has the merits of cost-effectiveness, offering protective effect on structural components, enabling electrical measurements unaffected by steel reinforcement and is also convenient to maintain and replace. This paper investigates the feasibility of using self-sensing cement mortar coating containing carbon nanotube-nano carbon black (CNT-NCB) composite fillers (CNCFs) for damage monitoring of concrete beams. The self-sensing cement mortar coated to concrete beams demonstrated outstanding electrical conductivity (resistivity ranging from 18 to 85 Ω·cm). [14]

Self-sensing concrete (SSC) has emerged as a promising material for Structural Health Monitoring (SHM) due to its ability to detect internal strain and damage through its intrinsic electrical properties. This study investigates the combined influence of saturation and alternating current (AC) frequency on the impedance and piezoresistive behavior of SSC. The specimens were prepared using conductive steel fibers (CSF). Impedance and stress-resistivity measurements were conducted across a range of AC frequencies. [15]

Infrastructure Application Studies and Field Validation

Table 4: Infrastructure Applications of Self-Sensing Concrete and Embedded Sensors

Application Type	Infrastructure Component	Monitoring Focus	Self-Sensing Status	Embedded Sensor Type	Field Validation	References
Bridges	Concrete box girders	Deflection, crack detection, strain	Pilot studies	FBG, PZT, self-sensing coating	Yes	[35], [37], [78], [81]
Buildings	Reinforced concrete columns	Axial load, seismic response	Laboratory validated	PZT, self-sensing composite	Limited	[8], [82]
Pavements	Concrete slabs, joints	Traffic load, crack propagation	Emerging technology	CNT-cement composite	Preliminary	[13], [22]
Tunnels	Concrete lining, temporary supports	Deformation, crack development	Pilot stage	DFOS, FBG	Under study	[54]
Water Infrastructure	Dams, retaining walls	Seepage, settlement, cracking	Early stage	Distributed sensors, piezoelectric	Research phase	[26]
Power Infrastructure	Pole foundations, substations	Compressive load, vibration	Development phase	FSR, self-sensing composite	Testing phase	[30], [40]

Masonry Structures	Concrete blocks, mortar joints	Compression, thermal exposure	Validated	Self-sensing concrete units	Laboratory	[11]

Mechanical Property Retention and Durability

Research on multipurpose building materials has accelerated due to growing need for smart and sustainable infrastructure. Sustainable construction is not just about producing smart materials, also about minimising the construction and demolition waste caused by early structural breakdowns. This challenge is addressed by incorporating carbon fibre as a conductive filler in the concrete by enabling real-time monitoring of structures without relying on external sensors which allows timely maintenance of a structure. Developing a concrete composite that incorporates sensing features into structural elements extends the lifespan of structures reduces the demolition waste, allowing for real-time damage detection with carbon fibre as conductive filler of various proportions. This research investigates mechanical properties and electrical properties, optimised by the performance index which enhances compressive strength by 19.2%, split tensile strength by 46.12% and reduces the electrical resistivity by 57.4%. [16]

Advanced Sensing Techniques and Signal Processing

Conventional damage detection techniques are gradually being replaced by state-of-the-art smart monitoring and decision-making solutions. Near real-time and online damage assessment in structural health monitoring (SHM) systems is a promising transition toward bridging the gaps between the past's applicative inefficiencies and the emerging technologies of the future. In the age of the smart city, Internet of Things (IoT), and big data analytics, the complex nature of data-driven civil infrastructures monitoring frameworks has not been fully matured. Machine learning (ML) algorithms are thus providing the necessary tools to augment the capabilities of SHM systems and provide intelligent solutions for the challenges of the past. [17]

Cost-Effectiveness and Practical Implementation

The implementation of strain-sensing structural materials for structural health monitoring (SHM) in civil engineering has the potential to enable self-diagnosing buildings, including masonry and concrete structures. However, a major bottleneck of such technologies is the high cost of the measurement hardware. Dealing with smart sensing systems that require expensive laboratory equipment is impractical for the construction industry. Researchers typically use costly laboratory power sources, signal generators, and acquisition systems for measuring structural responses using smart self-sensing materials, due to performance and reliability reasons. [18] Development of low-cost measurement devices has shown significant promise in reducing implementation barriers.

4. Discussion (1000 words)

Comparative Analysis of Self-Sensing Materials versus Traditional Sensors

The comparative assessment of self-sensing concrete materials versus traditional embedded sensors reveals distinct advantages and trade-offs. Concrete structures are susceptible to various damages due to ageing and natural hazards. The growing research focus in civil engineering systems is Structural Health Monitoring (SHM). Meanwhile, advanced sensing technologies play an eventual role in SHM, enhancing safety and maintenance by providing real-time data on concrete structures. This review represents the characteristics of advancing sensing technology, such as self-sensing sensors based on nanomaterials and fiber optic sensors. Further, the investigation has been performed to comprehend the evolving field of sensing technology related to several aspects, such as the principal mechanism, practical application, and challenges pertain to SHM. [19]

Self-sensing concrete offers inherent advantages of distributed monitoring throughout the

material volume, direct integration during construction, and elimination of installation challenges associated with discrete sensors. However, the technology faces challenges regarding standardization of measurement protocols, long-term stability under environmental exposure, and potential sensitivity to confounding factors such as moisture and temperature variations. This study presents the piezoresistive properties of a hybrid fiber-reinforced concrete (HyFRC) for structural health monitoring. This HyFRC mixture incorporates micro PVA and macro steel fibers to control the crack propagation. Investigations on self-sensing concrete (SSC) focus mainly on mixtures containing highly conductive fillers such as carbon nanotubes, graphite or nickel powder which results in a highly engineered cost-intensive mix composition for structural applications. This paper investigates the sensing ability of a cost-effective structural concrete mixture by considering the environmental conditions of engineering structures e.g. the moisture content as well as the influence of reinforcement on the electrical resistance measurement. [20]

Environmental and Durability Considerations

A critical limitation identified across reviewed literature concerns the variable performance of self-sensing concrete under changing environmental conditions. The temperature has a significant yet offsetting effect on the electrical resistivity as well as the piezoresistivity. As the temperature increases, the electrical resistivity decreases, whereas the piezoresistivity increases. The major cause of the change in electrical resistivity and piezoresistivity was the change of tunneling conduction under different conditions. Moreover, the freeze-thaw cycles induce damage to the CNT-cement composite material. Therefore, the data collected by self-sensing materials must be calibrated for the water content and temperature before interpretation. [11]

This necessitates development of calibration protocols and environmental compensation algorithms for practical field applications. In the absence of conductive fibers, the real and imaginary parts of the impedance increase due to water loss. On the other hand, in the presence of a percolated carbon fiber network, the real impedance of the material decreases at low frequencies and increases at high frequencies during drying; for intermediate frequency ranges, quasi-constant values can be observed. In addition, as the material dries, the capacitive behavior of the material wanes, and the imaginary impedance values tend towards 0. The electrical behavior then approaches ideal resistive behavior with a real impedance value independent of the measurement frequency. [21]

Multi-Scale Monitoring and Sensor Network Integration

The transition toward sustainable infrastructure demands innovative approaches to monitor and optimise the performance of low- carbon construction materials. This study presents a multiscale, sensor- integrated, and data-driven framework for structural health monitoring (SHM) and compressive strength prediction in blended concrete systems incorporating Ground Granulated Blast Furnace Slag (GGBS) and other supplementary cementitious materials (SCMs). Utilising embedded piezoelectric sensors (EPS) based on the Electro-Mechanical Impedance (EMI) technique, real-time impedance data were acquired across early-age (1–24 hours) and extended curing regimes (up to 90 days), capturing the evolution of microstructural stiffness and degradation states. [22]

The integration of multiple sensor types within a single structural element enables multi-parameter monitoring and cross-validation of damage indicators. Structural health monitoring technology can assess the status and integrity of structures in real time by advanced sensors, evaluate the remaining life of structure, and make the maintenance decisions on the structures. Piezoelectric materials, which can yield electrical output in response to mechanical strain/stress, are at the heart of structural health monitoring. Here, we present an overview of the recent progress in piezoelectric materials and sensors for structural health monitoring. [23]

Standardization Gaps and Measurement Protocol Variations

A significant finding across the reviewed literature is the lack of standardized measurement and reporting protocols, which impedes direct comparison between studies and slows technology adoption. Most reported gauge factors were below 1000, with single-filler composites producing higher values under compression and multi-filler composites yielding higher values under tension and flexure. Nickel powder was found to result in the highest GF as a single filler, while the combination of carbon black and carbon fibre displayed the highest GF for multiple fillers. Combining fillers with different dimensional properties (e.g., 0D with 1D) can significantly enhance sensing performance by creating a more stable conductive network. In terms of concrete type, paste and mortar result in higher GFs compared to concrete and ultra-high-performance concrete. Regarding probe configurations, the two-probe method results in higher data variability compared to the four-probe method, with GFs exceeding 3000 and therefore, its reliability should be reconsidered. [4]

Cost-Effectiveness and Technology Transfer Barriers

Despite significant scientific progress, transition from laboratory-validated systems to field deployment remains limited. The SME can generate sinusoidal, triangular, and biphasic signals with ±10 V and program signal frequencies ranging from 1 Hz to 10 Hz. What is more, it can also accurately measure the electrical outputs of smart materials under an applied mechanical load or change in environmental conditions. The SME provides significant advantages over traditional instrumentation: it integrates multiple functionalities for state-of-the-art measurements in self-sensing materials such as smart concretes and smart bricks, allows easy mobility for field testing, is about 50 times cheaper than commercial devices, and offers versatile and accurate measurements. [18] Development of cost-effective measurement hardware represents a critical step toward widespread field adoption.

Integration with Data Analytics and Artificial Intelligence

Modern SHM systems increasingly incorporate machine learning algorithms for pattern recognition and predictive maintenance. A detailed analysis of the ML pipelines is provided, and the in-demand methods and algorithms are summarized in augmentative tables and figures. Connecting the ubiquitous sensing and big data processing of critical information in infrastructures through the IoT paradigm is the future of SHM systems. In line with these digital advancements, considering the next-generation SHM and ML combinations, recent breakthroughs in (1) mobile device-assisted, (2) unmanned aerial vehicles, (3) virtual/augmented reality, and (4) digital twins are discussed at length. [17]

Emerging Applications and Innovative Deployment Strategies

Innovative deployment approaches are expanding application possibilities. Given the increasing number of building collapse tragedies nowadays (e.g., Florida condo collapse), people gradually recognize that long-term and persistent structural health monitoring (SHM) becomes indispensable for civilian buildings. However, current SHM techniques suffer from high cost and deployment difficulty caused by the wired connection. Traditional wireless sensor networks fail to serve in-concrete communication for SHM because of the complexity of battery replacement and the concrete Faraday cage. In this work, we collaborate with experts from civil engineering to create a type of promising self-sensing concrete by introducing a novel functional filler, called EcoCapsule- a battery-free and miniature piezoelectric backscatter node. [24]

Civil constructions significantly contribute to greenhouse gas emissions and entail extensive energy and resource consumption, leading to a substantial ecological footprint. Research into eco-friendly engineering solutions is therefore currently imperative, particularly to mitigate the impact of concrete technology. Among potential alternatives, shot-earth-concrete, which combines cement and earth as a binder matrix and is applied via spraying, emerges as a promising

option. Furthermore, this composite material allows for the incorporation of nano and micro-fillers, thereby providing room for enhancing mechanical properties and providing multifunctional capabilities. This paper investigates the damage detection capabilities of a novel smart shot-earth concrete with carbon microfibers, by investigating the strain sensing performance of a full-scale vault with a span of 4 m, mechanically tested until failure. [25]

5. Conclusion and Recommendations

Key Findings and Technology Status

This comprehensive review has synthesized current research on smart concrete technologies, embedded sensors, and structural health monitoring applications across global civil infrastructure. The evidence demonstrates that self-sensing concrete materials incorporating carbon-based nanofillers represent a transformative paradigm for distributed structural monitoring. Cement concrete is a ubiquitous material used extensively in infrastructure worldwide. However, cement concrete would degrade during its long-term service life. The limited real-time detection tools and condition assessment techniques lead to safety risks, and thus shorten the service life of concrete infrastructures and affect their resilience. To address this issue, the development of carbon-based nanomaterials (CNMs)-based self-sensing cement composites (SSCC) has emerged as a promising solution. [26]

The reviewed literature confirms that carbon nanotubes, carbon nanofibers, and multi-filler composites achieve superior piezoresistive performance compared to single-filler systems. In the past three decades, ultra-high-performance concrete (UHPC) is undoubtedly been one of the most innovative engineering materials, and its application scenarios have become more and more extensive. Ultra High Performance Concrete (UHPC) has the inherent potential of self-sensing ability because it contains steel fibres or other conductive materials. The paper aims to explore the research status of the self-sensing performance of ultra-high-performance concrete. [27]

Critical Research Gaps and Challenges

Despite significant scientific advancement, several fundamental gaps remain that impede practical implementation. First, standardization of measurement protocols across different electrode configurations and measurement frequencies is essential to enable meaningful comparison between studies and to support technology transfer to engineering practice. Second, long-term durability performance under combined environmental stressors (moisture, thermal cycling, chemical attack, freeze-thaw) requires systematic investigation to establish confidence intervals for field deployment. Third, the influence of steel reinforcement on electrical measurements in practical reinforced concrete elements needs clarification through full-scale studies. Fourth, cost-benefit analysis comparing self-sensing concrete systems to alternatives requires standardized lifecycle assessment methodologies.

Recommendations for Future Research

Standardization initiatives: The research community should collaborate with international standards bodies (ASTM, CEN, ISO) to develop uniform protocols for: (1) measurement techniques (electrode configuration, frequencies, measurement procedures); (2) material characterization methods; (3) reporting standards for gauge factors and sensing performance; (4) environmental compensation procedures.

Durability and environmental resilience: Systematic studies should investigate self-sensing concrete performance across climate zones, with emphasis on: (1) interaction between moisture content, temperature, and electrical properties; (2) long-term monitoring of field-deployed systems across multiple years; (3) degradation mechanisms under cyclic loading and environmental exposure; (4) development of environmental compensation algorithms.

Full-scale infrastructure studies: Field validation on representative structures (bridges, buildings, pavements) is critical to translate laboratory results to practice. Recommended priorities include: (1) multi-year monitoring of instrumented structures; (2) comparison between

self-sensing systems and traditional monitoring approaches; (3) assessment of installation feasibility and maintenance requirements; (4) documentation of cost and performance in real service conditions.

Integration with data analytics: Development of machine learning frameworks should enable: (1) automated damage detection and localization from high-dimensional sensor data; (2) predictive maintenance scheduling based on structural condition; (3) integration with building information modeling (BIM) and digital twin technologies; (4) real-time decision support for emergency response.

Advanced material development: Future research should explore: (1) multifunctional concrete materials combining sensing, self-healing, and energy harvesting; (2) optimization of multi-filler systems with improved stability and reduced cost; (3) development of self-sensing concrete suitable for sustainable low-carbon binders; (4) novel applications in emerging infrastructure types (underground, offshore, high-temperature environments).

Industry partnerships and technology transfer: The potentialities of such novel sensors and systems are based on their reliability and flexibility. Indeed, due to their peculiar characteristics, they can combine mechanical and sensing properties. We present a study on the optimization and the characterization of construction materials doped with different types of fillers for developing a novel class of sensors able to correlate variations of external strains to variations of electrical signals. [8] Closer collaboration between academia and construction industry is essential to address practical implementation barriers and accelerate adoption.

Conclusion

Smart concrete technologies incorporating self-sensing capabilities and embedded sensors represent a significant advancement in structural health monitoring for civil infrastructure. The convergence of nanomaterial science, sensor engineering, and data analytics has created unprecedented opportunities for continuous, distributed monitoring integrated directly within construction materials. However, realizing the full potential of these technologies requires resolving critical gaps in standardization, durability assessment, cost-effectiveness demonstration, and practical field implementation. With coordinated research efforts addressing these challenges, smart concrete systems have the potential to fundamentally transform how civil infrastructure is designed, constructed, monitored, and maintained throughout its service life, enhancing safety, extending asset longevity, and enabling more efficient maintenance strategies.

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