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Toward Self-Sensing Roads: A Systematic Review of Embedded IoT Sensors for Pavement Monitoring and Maintenance

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Abstract—Recent advances in smart materials and sensing technologies have enabled pavements to evolve from passive structural elements into self-sensing infrastructure capable of monitoring traffic loads, structural condition, and environmental effects in real time. A growing body of research has explored conductive materials, embedded sensors, and self-sensing mechanisms for pavement monitoring, while parallel efforts have examined IoT-based data acquisition and analytics frameworks. However, existing review studies often address these topics from isolated perspectives, with limited integration between material-level sensing behavior, underlying self-sensing mechanisms, and system-level IoT architectures. This paper presents a comprehensive review of self-sensing road technologies by synthesizing insights from existing review literature and representative experimental studies. The review first summarizes key embedded sensing approaches and smart materials used in pavements, followed by an in-depth discussion of self-sensing mechanisms related to strain, damage, temperature, and moisture monitoring. Building on this foundation, the paper examines IoT architectures and system-level considerations required to support continuous data acquisition, communication, and integration with pavement management systems. Key challenges related to durability, scalability, power management, data interpretation, and long-term deployment are identified, and future research directions are outlined. By bridging material-level innovations with system-level IoT perspectives, this review provides a unified framework for understanding the current state and future potential of self-sensing pavements. The findings aim to support the development of resilient, intelligent, and sustainable road infrastructure capable of meeting the demands of modern transportation networks.

Index Terms—Smart Pavements, Self-Sensing Materials, Embedded IoT Sensors, Real-Time Road Monitoring, Piezoresistive Asphalt, Fiber-Optic Sensing, Carbon Nanotubes, Graphene Nanoplatelets and Pavement Health Monitoring

I. INTRODUCTION

CIVIL infrastructure—including bridges, buildings, water pipelines, offshore platforms, and oil storage tanks—operates in dynamic, harsh environments characterized by large temperature fluctuations and elevated CO₂, which accelerate material degradation over time [1], [2], [3]. Consequences include crack initiation, crevice formation, and a gradual loss of structural capacity. Early localization and sizing of defects are therefore critical to avoid catastrophic failures. Yet periodic visual inspections and manual

assessments are inherently limited in detecting incipient damage, and most conventional destructive and non-destructive techniques do not provide continuous condition data, underscoring the need for advanced monitoring approaches that leverage smart, sensor-enabled materials [4].

Smart technologies—IoT, pervasive sensorization, and AI—are reshaping pavement data collection and analysis, enabling smarter, more efficient asset management aligned with UN sustainability goals [5]. By delivering continuous, high-quality real-time streams, smart pavements improve Pavement Management Systems (PMS) and support faster, evidence-based decisions [6]. Central to this shift are pavement-embedded smart sensors that convert passive roads into responsive infrastructure by sensing, analyzing, and transmitting traffic, environmental, and structural-health data in real time.

Systematic pavement monitoring is essential for collecting reliable data and insights for performance assessment and analytics [7]. Conventional “auscultation” campaigns usually rely on visual inspections and specialized survey vehicles to measure bearing capacity and surface condition. However, these methods are labor-intensive, time-consuming, expensive, and often unable to capture early-stage micro-damage or its progression. These limitations have motivated intensive research over recent decades into advanced sensing technologies and non-destructive testing (NDT) methods that can monitor traffic loads and pavement health more effectively, ideally providing continuous or real-time information [7], [8].

Embedded sensors in asphalt pavements make it possible to continuously measure stress, strain, and deflection, providing the data needed for modern PMS and real-time decision support tools, including Digital Twins [9]. Traditional devices—such as strain gauges, LVDTs, accelerometers, load cells, geophones, and thermocouples—have recently been complemented by wireless sensor networks and fiber-optic technologies, which have shown strong potential in field applications [8], [10]. Their feasibility has been demonstrated on several full-scale facilities, including the NCAT test track, the Virginia Smart Road, MnRoad, and the PEGASE platform [11]. However, these intrusive sensors face important durability challenges: they must survive high temperatures and stresses during construction, then endure heavy traffic and harsh environmental conditions throughout service life, and any mismatch between the sensor and asphalt mixture can create mechanical discontinuities that may contribute to premature pavement failure [12].

Smart pavement sensing spans three complementary tiers. (1) Smart composites—e.g., piezoresistive or conductive mixes embedded in the matrix—add self-sensing (and potentially self-healing) capabilities that extend service life and cut maintenance and rehabilitation needs [13]. (2) Surface-mounted sensors—such as microphones and other recorders—capture vibrations, noise, and temperature for rapid condition checks and are easy to install and maintain for continuous monitoring [14]. (3) In-pavement sensors—including fiber-optic strain/temperature sensing and stress gauges—measure internal responses (strain, moisture, subsurface damage) to enable early failure detection and to assess materials/designs under real loads over time [15].

In situ sensing for pavements has become a major focus in road engineering because it enables structural health monitoring (SHM)—the real-time tracking of internal deformation and damage in civil infrastructure. Active SHM systems use sensors, data acquisition and communication units, and diagnostic/decision modules to detect defects and monitor strain, temperature, and other indicators in real time, supporting timely and effective maintenance decisions, as shown in Fig. 1.

In recent years, a number of review studies have explored smart pavements, pavement sensing technologies, wireless sensor networks, and IoT-enabled monitoring systems from different viewpoints. While some reviews concentrate on data collection and analytics within pavement management systems, others focus on sensing materials, structural health monitoring methods, or intelligent transportation infrastructure. As a result, these studies often examine individual elements of smart pavement systems rather than presenting an integrated perspective centered on embedded, in-pavement IoT sensors and their role within operational pavement management and decision-support frameworks. Consequently, broader system-level considerations—such as overall architecture, long-term deployment challenges, and the practical use of embedded sensing in real-world PMS—remain scattered across the existing review literature.

Although several reviews address smart data collection and analytics for pavements [6], [16], a targeted synthesis of state-of-the-art embedded smart technologies is still needed. This paper fills that gap by surveying embedded sensor systems—their underlying technologies, applications, and anticipated impacts on pavement management—while detailing technical nuances, practical challenges, and future research directions. We emphasize integration with pavement management systems (PMS) and outline a clear roadmap for adopting embedded sensing in practice to enable more resilient, intelligent, and sustainable road infrastructure.

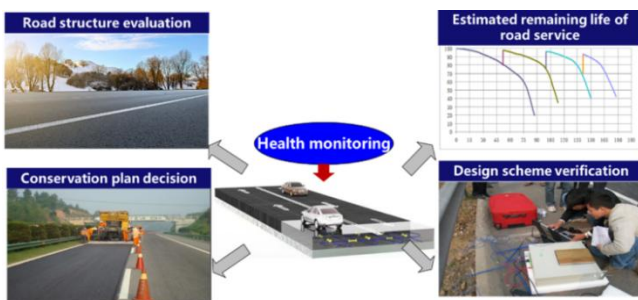


Fig. 1: Pavement health monitoring

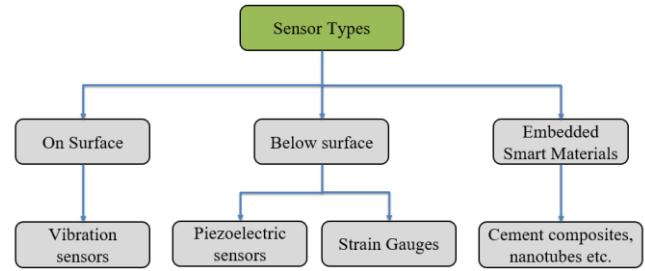


Fig. 2: Pavement sensing types

II. RELATED WORK

A) Representative Embedded Self-Sensing Technologies for Smart Pavements

1). Weigh-In-Motion Sensing

Birgin et al. highlight the need for cost-effective Weigh-In-Motion (WIM) solutions in smart pavements, especially for bridge condition monitoring. They propose a WIM algorithm that leverages conductive cementitious materials, inferring axle passages from resistance changes to estimate axle loads and classify vehicles. Numerical simulations validate the method across multiple truck types and show robust accuracy even with noise levels up to 5% of the signal peak [17].

2). Graphite-Enhanced Cement-Based Composite Sensing

Birgin et al. developed a low-cost, scalable graphite-enhanced cement-based composite for Weigh-In-Motion (WIM) sensing, indicating strong potential for practical traffic-monitoring deployments [18]. In related work, they introduced an eco-friendly synthetic binder (EVIzero) with carbon-microfiber inclusions that imparts piezoresistive behavior, enabling strain sensing and vehicle-load detection without disrupting traffic. The composite was reported to be cost-effective, durable, straightforward to implement, and precise, with a tailored electrode layout that reduces the number of required sensors [19].

3). Cement-Based Sensor Using Rubber Fibres

Smart materials extend beyond flexible pavements. Dong et al. developed a cement-based sensor using layer-distributed conductive rubber fibers to enhance structural health monitoring. They examined constituents, fabrication, electrical behavior, self-sensing efficiency, repeatability, and compressive strength, finding that the fibers markedly improved conductivity. The resulting rubber-fiber cementitious composites show strong potential for concrete SHM and pavement traffic monitoring, offering intrinsic sensing, durability, and minimal impact on mechanical performance [13].

4). Nano-Material Sensing

Multiple studies investigate Carbon Nanotubes (CNTs), Graphene Nanoplatelets (GNPs), and CNT-GNP hybrids for both rigid and flexible pavements. Xin et al. evaluated CNT/epoxy composites, showing promising strain-sensor performance for asphalt monitoring: CNTs increased tensile strength and elastic modulus, though excessive loading caused agglomeration and degraded mechanics. In follow-up work, they dispersed three CNT types (varying specific surface area) and GNPs in epoxy, finding that CNT-GNP hybrids formed superior conductive networks and dispersed

more uniformly than CNTs alone, enhancing electrical response and strain-sensing. Laboratory validation—including three-point bending on asphalt beams with embedded sensors—confirmed durability and high measurement accuracy [20], [21].

5). Self-Sensing Asphalt Mixtures

Gulisano et al. developed and evaluated self-sensing asphalt mixtures incorporating coarse aggregates, fine electric-arc-furnace slag (EAFS), polymer-modified bitumen, and graphene nanoplatelets (GNPs). Electromechanical tests showed a linear relation between applied stress and electrical response, and wavelet-transform analysis indicated robust long-term and damage-sensing performance—supporting real-time pavement health monitoring [22]. Ozbulut et al. produced GNP-reinforced mortars (Portland cement with ASTM-graded sand), observing that GNP contents >5% significantly reduced electrical resistivity, with 7.5% yielding optimal self-sensing behavior; these composites are strong candidates for continuous structural health monitoring [23].

B) Summary of Observed Research Gaps

The reviewed literature demonstrates substantial progress in the development of embedded self-sensing materials and sensor technologies for pavement monitoring. Studies on conductive cementitious composites, nanomaterial-enhanced sensors, and self-sensing asphalt mixtures confirm that pavements can reliably capture traffic loads, strain, and damage-related responses from within the structure [17]–[23]. At the same time, existing review papers tend to discuss these sensing approaches either at the material level or within narrowly defined application contexts [6], [16].

However, when viewed collectively, several gaps become apparent. Most studies emphasize sensing performance without sufficiently addressing how these technologies integrate into complete IoT-based monitoring systems, including data acquisition, communication, and long-term operation within pavement management frameworks. Issues such as system-level architecture, interoperability, scalability, and sustained field deployment are often treated only superficially or remain fragmented across the literature [6], [16]. These limitations highlight the need for a consolidated, IoT-centric synthesis that bridges material-level sensing innovations with system-level design considerations and decision-support tools for self-sensing road infrastructure.

Although existing review studies have examined smart pavement technologies and IoT-based monitoring from different viewpoints, they largely address sensing materials, mechanisms, and system frameworks in isolation. Consequently, the connection between material-level self-sensing behavior and system-level IoT architectures that support long-term pavement management remains weakly explored. This review addresses this gap by jointly synthesizing embedded self-sensing mechanisms and IoT system considerations within a unified framework for self-sensing road infrastructure.

Table I: List of investigated literature works for smart materials

Smart Material Type	Application	Ref.
Graphite-Enhanced Cement Composites	Weight in motion sensing	[19]

Conductive Rubber Fiber Cement	Traffic monitoring	[19]
Carbon Nanotube (CNT)	Structural Health Monitoring (SHM)	[24]
CNT-GNP Hybrid Composites	Strain monitoring in asphalt	[24]
CNT-Cement Composites	Improved electrical conductivity	[24]
CNT Concrete Sensors	Piezoresistivity under fatigue, water, temp effects	[25]
GNP-Reinforced Mortar	Vehicle detection under real traffic	[25]
Bitumen with Magnetic Particles	Stress and damage sensing	[24]
CNTs & Graphene as Microwave Absorbers	Real-time SHM, reduced resistivity	[24]
Conductive Fibers + Electromagnetic Heating	Temperature-adaptive pavements	[19]
Photocatalytic Agent (OXE-CHI)	Enhanced asphalt healing via microwave	[25]
Microcapsules with Rejuvenator	Deep crack healing	[19]
Microvascular Structures with Oil-Based Rejuvenator	UV-based self-healing asphalt	[19]

III. SELF-SENSING MECHANISM AND ASSESSMENT

A. Self-Sensing Asphalt Mixtures

Recent studies show that conductive asphalt mixtures can act as effective self-sensing materials, where changes in stress or strain are captured through variations in electrical resistance. Wu et al. [26] linked these resistance changes to proximity effects between conductive particles, microcrack formation, and disruption of conductive paths caused by aggregate motion. Liu et al. reported that graphite - carbon fiber mixtures can reach high gauge factors (GF =11 at 1.5 MPa and up to 350 at 0.7 MPa), highlighting their strong strain-sensing potential [27]. Other works demonstrated reliable sensing responses under different loading modes for mixtures with carbon nanofibers, as well as for asphalt containing EAF steel slag and graphene nanoplatelets. For weigh-in-motion and traffic monitoring, however, sensitivity must remain stable over time: Liu et al. [28] showed that mixtures with very high graphite content lose GF over repeated loading cycles, whereas mixtures with lower graphite content maintain their sensitivity, suggesting that long-term performance depends on the mixture’s conductive network. Building on this, Gulisano et al. [29] combined piezoresistive carbon-fiber asphalt with digital signal processing and an artificial neural network, achieving a load-classification accuracy of 0.977 and demonstrating the promise of these materials for future smart pavement and WIM applications.

B. Damage Sensing

Self-sensing asphalt materials can also act as “damage sensors,” because their electrical resistance changes as microcracks form and propagate within the mixture. Although this mechanism is distinct from classic strain-based piezoresistivity, it is crucial for early damage detection and continuous pavement health monitoring: as cracks cut conductive paths, electrical resistance generally increases, so tracking fractional change in resistance (FCR) over time can

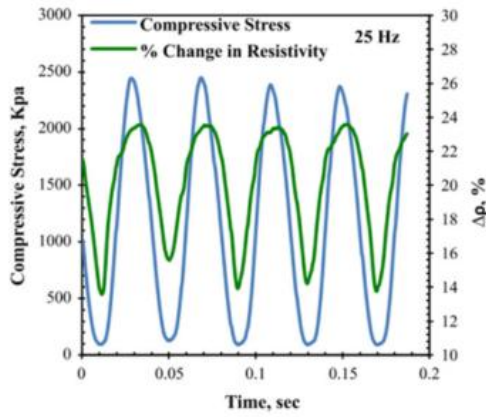


Fig. 3: Piezoresistive response of asphalt mixtures under various loading conditions. Adapted from [13].

signal emerging distress and support preventive maintenance. Damage-sensing performance is typically evaluated in tests carried out to failure, and several studies have shown clear links between electrical response and structural degradation. Liu et al. [28] reported three characteristic FCR phases during fatigue loading of graphite-carbon fiber asphalt: initial compaction and reduced resistance, a quasi-stable phase with competing compaction and microcracking, and finally a sharp resistance increase as cracks dominate and the conductive network collapses. Similar multi-stage resistance trends and strong correlations between displacement, crack growth, and resistivity were observed under tensile and fatigue loading in graphite-carbon fiber mixtures and carbon fiber-graphite concretes [30]. Mixtures with carbon nanofibers, EAFS + graphene nanoplatelets, and carbon fiber with iron tailings have likewise shown robust damage-sensing behavior, with resistance evolution closely tracking crack formation and propagation. Advanced signal-processing methods, such as continuous wavelet transform and multiresolution analysis, further enhance the ability to interpret these electrical signals and identify cracking events [31]. However, fully exploiting this capability will require future development of statistical and predictive models that relate FCR to pavement structural condition so that electrical response can be used as a practical pavement condition index in real-time health monitoring systems. This makes damage-sensing especially valuable for triggering condition-based inspections and maintenance before visible surface distress emerges.

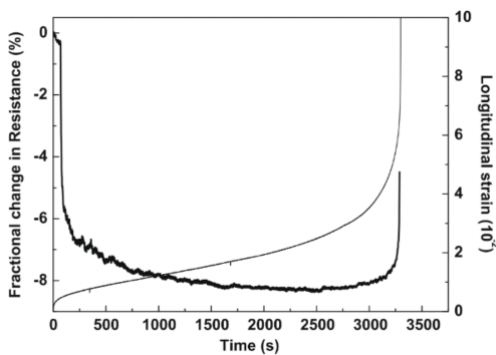


Fig. 4: Damage sensing during a compressive fatigue test, showing longitudinal strain (thin curve) and FCR (thick curve). Adapted from [22].

C. Temperature and Moisture Sensing

Conductive asphalt mixtures may also be able to sense temperature and moisture, offering a built-in alternative to conventional embedded devices such as thermocouples and thermistors for pavement temperature monitoring. If asphalt can be designed with reliable thermoresistive behavior—where electrical resistance changes predictably with temperature—it would not only remove the need for separate thermal sensors, but also allow correction of temperature effects when interpreting piezoresistive or damage-sensing signals; this behavior is typically described through the Temperature Coefficient of Resistance (TCR). Experimental results are mixed: Wu et al. [32] and Sun et al. [33] observed a Positive Temperature Coefficient (PTC) in conductive asphalt, where resistance increases with temperature, likely because bitumen expansion separates conductive particles. In contrast, studies on cementitious composites have reported Negative Temperature Coefficient (NTC) behavior, with resistance decreasing as temperature rises due to reduced tunneling distance and enhanced charge transport in the conductive network. Chen et al. [34] even found both PTC and NTC regimes in carbon-fiber-reinforced concrete depending on temperature range, underscoring that the thermoresistive behavior of conductive asphalt is still not fully understood and requires further research. Moisture is another critical factor, as it degrades asphalt-aggregate adhesion and can cause stripping and moisture-related damage; while Ground-Penetrating Radar (GPR) is currently used to infer moisture conditions in pavements, intrinsically moisture-sensing asphalt would enable continuous monitoring in service. Although moisture sensors based on nano-modified Portland cement have been developed [35], comparable moisture-sensing capabilities in asphalt mixtures have yet to be systematically investigated.

IV. IoT ARCHITECTURES AND SYSTEM-LEVEL INTEGRATION FOR SELF-SENSING ROADS

The self-sensing mechanisms discussed in the previous section demonstrate that pavements can reliably capture strain, damage evolution, temperature, and moisture-related information from within the material itself. However, realizing the full value of these capabilities requires more than material-level innovation. To function as intelligent infrastructure, self-sensing pavements must be embedded within robust IoT architectures that support data acquisition, communication, processing, and integration with pavement management systems. Existing review papers frequently acknowledge this requirement, yet system-level integration is often discussed only at a conceptual level, leaving important practical considerations insufficiently addressed [6], [16].

A) Layered IoT Architecture for Self-Sensing Pavements

IoT-enabled pavement monitoring systems are commonly described using a layered architecture. At the lowest level, the sensing layer consists of embedded self-sensing materials or in-pavement sensors that convert mechanical or environmental stimuli into electrical signals. These signals are handled by a data acquisition layer responsible for signal conditioning, digitization, and basic preprocessing. A communication layer then enables data transmission to roadside units, gateways, or centralized servers, while higher

layers support data storage, analytics, visualization, and integration with pavement management systems. This layered view is widely referenced across smart pavement and structural health monitoring reviews as a useful conceptual framework [6], [16]. Despite its broad adoption, the layered architecture is rarely examined in detail with respect to pavement-specific constraints. In particular, the interactions between layers—and how they are affected by harsh environmental conditions, limited accessibility, and long service life requirements—remain insufficiently explored in the review literature.

B) Data Acquisition and Communication Considerations

Embedded pavement sensors operate under challenging conditions that directly influence data acquisition and communication strategies. Continuous monitoring, especially under traffic loading, can generate large volumes of data, while communication bandwidth, latency, and reliability may be limited. Many studies rely on wireless sensor networks or short-range communication technologies to transmit data from embedded sensors to external receivers, and these approaches are frequently discussed in existing reviews [6], [10]. However, review papers often treat communication protocols independently of sensing mechanisms and material behavior. As a result, important trade-offs—such as balancing data resolution against transmission frequency, energy consumption, and long-term reliability—are not consistently addressed from a holistic system perspective. This disconnect remains a key limitation in translating laboratory-scale sensing solutions into deployable IoT systems.

C) Power Supply and Energy Constraints

Power supply is consistently identified as one of the most critical challenges for embedded IoT-based pavement monitoring systems. Once sensors are installed within pavement layers, routine maintenance or battery replacement becomes impractical. Consequently, low-power system design and energy harvesting approaches are frequently proposed as potential solutions in the literature [6], [16]. While power limitations are widely acknowledged in review studies, there is limited synthesis on how power constraints shape overall system architecture, sensing frequency, and communication strategies. In many cases, power management is discussed as an isolated issue rather than as a central design constraint that must be addressed across all system layers.

D) Integration with Pavement Management Systems

A primary motivation for deploying IoT-enabled self-sensing pavements is their potential to enhance pavement management systems by providing continuous, high-resolution condition data. In principle, such data can support predictive maintenance, performance-based decision-making, and the development of digital twins for road infrastructure [9]. In practice, however, the integration of sensor data into operational pavement management workflows remains underdeveloped. Many studies focus on demonstrating sensing feasibility without clearly explaining how collected data informs maintenance planning, condition indices, or asset management strategies. Existing review papers similarly emphasize the promise of data-driven pavement management but provide limited guidance on data

standardization, interoperability, and implementation pathways [6], [16].

E) Toward Integrated, Scalable Self-Sensing Road Systems

Taken together, the reviewed literature reveals a persistent gap between material-level sensing innovations and fully integrated IoT-based pavement monitoring systems. While individual components—such as self-sensing materials, data acquisition units, and communication technologies—have been extensively studied, their coordinated operation within scalable and reliable system architectures remains an open challenge [6], [16]. Addressing this gap requires an IoT-centric perspective that explicitly links sensing mechanisms with system architecture, power management, data handling, and decision-support tools. Such integration is essential for transitioning self-sensing pavements from experimental demonstrations to practical infrastructure capable of supporting long-term, network-scale monitoring.

V. SELF-SENSING CHALLENGES, OPEN ISSUES, AND FUTURE RESEARCH DIRECTIONS

The system-level perspective discussed in the previous section highlights the strong potential of IoT-enabled self-sensing pavements, but it also makes clear that several challenges still stand in the way of their widespread adoption. When existing review papers and representative studies are considered together, it becomes evident that these challenges are not confined to individual sensors or materials. Instead, they emerge from the way sensing technologies, self-sensing mechanisms, and IoT systems interact within real pavement environments. Addressing these open issues is therefore essential if self-sensing pavements are to move beyond experimental demonstrations and become reliable, long-term infrastructure solutions.

A) Durability and Long-Term Performance

One of the most consistently highlighted concerns in literature is the long-term durability of embedded self-sensing materials and sensors. Pavements expose sensing components to harsh conditions, including high construction temperatures, repeated traffic loading, moisture penetration, and environmental aging. While many studies report encouraging results under laboratory testing or short-term field trials, far fewer examine how sensing performance evolves over the full-service life of a pavement. As noted across existing reviews, the lack of long-term field evidence remains a key obstacle to large-scale implementation.

B) Scalability and Network-Level Deployment

Most self-sensing pavement studies focus on limited test sections or pilot installations, which are valuable for demonstrating feasibility but offer limited insight into network-level deployment. Scaling these systems across entire road networks introduces challenges related to sensor density, data volume, communication reliability, and maintenance planning. Although review papers frequently emphasize the promise of IoT-enabled pavements for network-scale monitoring, practical guidance on deployment strategies, cost considerations, and long-term operation is still relatively scarce.

C) Data Interpretation and Decision Support

Another important challenge lies in translating sensor measurements into information that can directly support pavement management decisions. Many studies successfully capture strain, damage progression, or environmental effects, yet the link between these measurements and maintenance or rehabilitation actions is often weak. Existing reviews regularly acknowledge the importance of data-driven pavement management systems, but they provide limited discussion on data fusion, uncertainty handling, or standardized indicators that practitioners can readily use. Without such frameworks, the practical impact of continuous sensing remains constrained.

D) Power Supply and Energy Management

Power availability continues to be a limiting factor for embedded IoT sensing systems in pavements. Once sensors are installed, access for battery replacement or repair becomes extremely difficult. As a result, low-power system design and energy harvesting are frequently proposed as potential solutions. However, the reviewed literature suggests that these approaches are still in early stages of development and have not yet been widely validated under real pavement conditions. Power constraints therefore continue to influence sensing frequency, communication strategies, and overall system reliability.

E) Integration Across Research Layers

Perhaps the most significant open issue identified through this review is the limited integration across research layers. Existing review studies often address sensing materials, self-sensing mechanisms, or IoT architecture separately, with relatively little effort to connect these elements into a cohesive system. As a result, material-level innovations are not always evaluated within realistic IoT architectures, and system-level frameworks may overlook fundamental sensing and durability constraints. Bridging this divide represents a major opportunity for future research and is essential for realizing fully integrated self-sensing road systems.

F) Future Research Directions

Building on the collective insights of existing review papers and representative studies, future research should increasingly focus on integrated approaches that link sensing materials, self-sensing mechanisms, and IoT system design. Long-term field validation under realistic traffic and environmental conditions will be particularly important for building confidence in these technologies. In addition, greater emphasis is needed on scalable architecture, standardized data workflows, and seamless integration with pavement management systems. Progress in these areas will be critical for enabling self-sensing pavements to contribute meaningfully to intelligent, resilient, and sustainable transportation infrastructure.

Table II: From Self-Sensing Pavements to Maintenance Decisions: An End-to-End Review of Sensors, IoT, and Analytics

Review category	Main emphasis	Gap	What this review contributes
Sensor-technology reviews	Sensor types, measurement principles, and use-cases	Isolated sensing focus	Sensors-to-maintenance pathway

Self-sensing material/composite reviews	Material design, self-sensing, lab performance	Limited field robustness	Material-to-system feasibility
Wireless sensor network / IoT-infrastructure reviews	Connectivity, architecture, communication, data transfer	Conceptual, not deployable	Pavement IoT blueprint
Pavement management / decision-support reviews	How monitoring supports maintenance	Assumes reliable data	Reliable data to PMS
AI/analytics-focused smart road reviews	Data-driven detection prediction and algorithms	Ignores embedded constraints	Analytics grounded in reality
This review	Integrated end-to-end view (self-sensing, IoT and deployment)		End-to-end unified synthesis

VI. CONCLUSION

This review has examined the evolving field of self-sensing pavements through an integrated perspective that brings together embedded sensing materials, self-sensing mechanisms, and IoT-based system architectures. By synthesizing insights from existing review papers alongside representative studies, the paper highlights how advances in conductive materials, piezoresistive behavior, and in situ sensing have enabled pavements to monitor traffic loads, structural response, and environmental effects directly from within the material.

Beyond individual sensing approaches, this work emphasizes the importance of system-level integration for realizing the full potential of self-sensing roads. While prior reviews have often addressed sensing technologies, mechanisms, or IoT frameworks in isolation, this study bridges these layers by explicitly connecting material-level behavior with data acquisition, communication, and pavement management systems. In doing so, it addresses a key gap in the review literature and provides a unified framework for understanding how self-sensing pavements can function as part of intelligent transportation infrastructure.

The review also identifies several challenges that must be addressed to support widespread adoption, including long-term durability, scalability, power management, data interpretation, and integration across research layers. Addressing these challenges will require coordinated research efforts that move beyond isolated demonstrations toward long-term, system-oriented solutions validated under real traffic and environmental conditions.

Overall, this review contributes a comprehensive and integrated synthesis of self-sensing pavement technologies and their role within IoT-enabled monitoring systems. By clarifying current capabilities, limitations, and research directions, it aims to support future developments toward resilient, intelligent, and sustainable road infrastructure capable of meeting the demands of modern transportation networks.

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