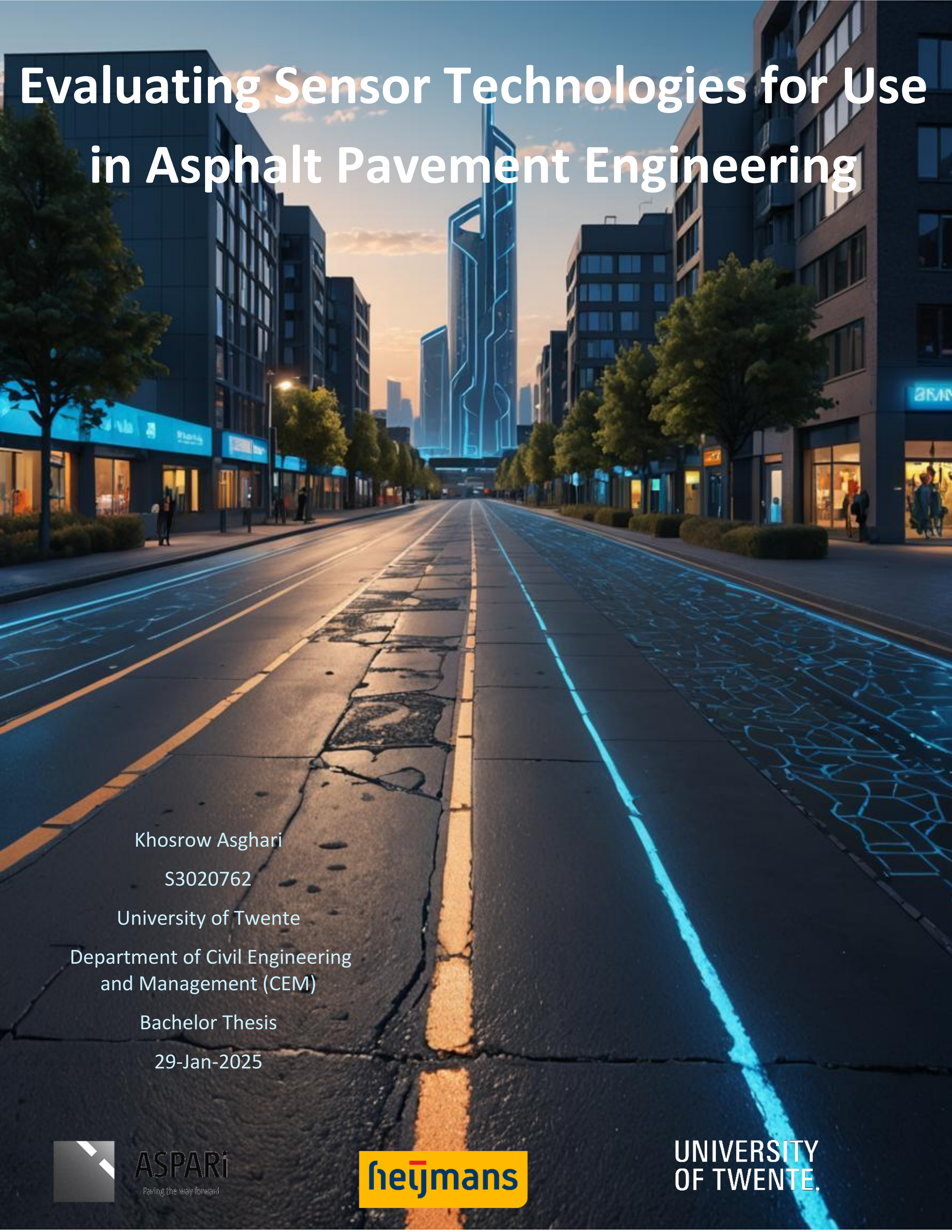

Evaluating Sensor Technologies for Use in Asphalt Pavement Engineering

Khosrow Asghari

S3020762

University of Twente

Department of Civil Engineering and Management (CEM)

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ASPARi
Paving the way forward

heijmans

UNIVERSITY OF TWENTE.

Abstract

The need for durable, sustainable pavements under increasing traffic loads focuses attention on the need for innovative monitoring and maintenance solutions for asphalt infrastructure. Traditional monitoring methods cannot provide the real-time, continuous data that will be needed to address modern challenges. Advanced sensor technologies discussed in this paper offer opportunities for revolutionizing asphalt pavement engineering. Carried out in cooperation with Heijmans, one of the leading construction firms, the research focuses on the use of state-of-the-art systems in monitoring pavement health: fiber optic sensors, self-sensing materials, and wireless sensor networks.

A combination of systematic literature review and multi-criteria analysis was therefore conducted to evaluate the sensor technologies based on sensitivity, accuracy, cost, durability, sustainability, and readiness level. FBG and DOFS sensors were identified to be blessed with high accuracy and sensitivity during the monitoring process of stress, strain and temperature in real time. Of these, self-sensing asphalt with the inclusion of conductive additives like carbon nanotubes and fibers presented intrinsic capabilities for structural deformation and damage detection without external sensors. Wireless sensors such as SmartRock and Smart Aggregates provided localized monitoring of the stress conditions with data transmission; however, these require further field validation to demonstrate robustness for practical applications.

Key findings are that integration into asphalt is challenging with regard to durability in extreme environmental/operational conditions and the cost barrier to large-scale deployment. Even within such limitations, the research identifies promising pathways to advance construction quality and prolong pavement lifespan. This will involve recommendations for optimization in sensor placement strategy, standardization of embedding techniques, and utilization of data analytics for predictive maintenance. It shows in the study the urgency for combined efforts between academia and industry to remove the existing obstacles and accelerate intelligent sensing systems applied in asphalt pavement engineering.

This research contributes to the advancement of sustainable and smart infrastructure solutions, paving the way for improved road performance, reduced maintenance costs, and enhanced transportation safety.

Abstract

De behoefte aan duurzame, duurzame wegen onder toenemende verkeersbelasting richt de aandacht op de noodzaak van innovatieve monitoring- en onderhoudsoplossingen voor asfaltinfrastructuur. Traditionele methoden voor monitoring kunnen niet de realtime, continue gegevens leveren die nodig zullen zijn om moderne uitdagingen aan te pakken. Geavanceerde sensortechnologieën die in dit artikel worden besproken, bieden kansen om de asfaltwegenbouw te revolutioneren. Uitgevoerd in samenwerking met Heijmans, een van de toonaangevende bouwbedrijven, richt het onderzoek zich op het gebruik van state-of-the-art systemen voor het monitoren van de conditie van wegdek: glasvezelsensoren, zelfvoelende materialen en draadloze sensornetwerken.

Een combinatie van systematisch literatuuronderzoek en multicriteria-analyse werd daarom uitgevoerd om de sensortechnologieën te evalueren op basis van gevoeligheid, nauwkeurigheid, kosten, duurzaamheid, duurzaamheid en gebruiksklaarheidsniveau. FBG- en DOFS-sensoren bleken een hoge nauwkeurigheid en gevoeligheid te hebben tijdens het monitoren van spanning, vervorming en temperatuur in realtime. Van deze technologieën bleek zelfvoelend asfalt met de toevoeging van geleidende additieven, zoals koolstofnanobuisjes en vezels, intrinsieke capaciteiten te hebben voor het detecteren van structurele vervorming en schade zonder externe sensoren. Draadloze sensoren zoals SmartRock en Smart Aggregates boden lokale monitoring van de spanningscondities met gegevensoverdracht; echter, deze vereisen nog verdere veldvalidatie om robuustheid voor praktische toepassingen aan te tonen.

Belangrijke bevindingen zijn dat integratie in asfalt een uitdaging vormt met betrekking tot duurzaamheid in extreme milieu- of operationele omstandigheden en de kostenbarrière voor grootschalige implementatie. Ondanks dergelijke beperkingen identificeert het onderzoek veelbelovende routes om de bouwkwaliteit te verbeteren en de levensduur van het wegdek te verlengen. Dit omvat aanbevelingen voor optimalisatie in sensorplaatsingsstrategieën, standaardisatie van inbeddingstechnieken en het gebruik van data-analyse voor voorspellend onderhoud. Het onderzoek toont de urgentie aan van gezamenlijke inspanningen tussen academische instellingen en de industrie om bestaande obstakels te overwinnen en intelligente sensorsystemen voor asfaltwegenbouw te versnellen.

Dit onderzoek draagt bij aan de vooruitgang van duurzame en slimme infrastructuuroplossingen, en effent de weg voor verbeterde wegprestaties, lagere onderhoudskosten en verhoogde verkeersveiligheid.

Colophon

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Report type	Bachelor Thesis
Title	Evaluating Sensor Technologies for Use in Asphalt Pavement Engineering
Date	29-Jan-2025
Author information:	
Author	Khosrow Asghari
Study	Bachelor of Civil Engineering
Institution	University of Twente
Email	K.asghari@student.utwente.nl, Khosrow.asghari@hotmail.com
Internal supervisors:	
Institution	University of Twente
Department	Asphalt Paving Research and Innovation (ASPARi)
Supervisor	DR. S.R. Miller (Seirgei)
Email	s.r.miller@utwente.nl
External supervisors:	
Company	Heijmans Infra, Asfalttechniek
Supervisor	Ir. Frits Stas
Email	fstas@heijmans.nl

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1. Introduction

In the last decades, the demand for durable and high-performing pavements has substantially escalated, driven by the expanded length of road networks and the growing truck traffic loads that the networks must carry. Not only does pavement failures cause expensive repairs, but it also can be a safety and transportation flow disruption. Traditional methods of pavement monitoring, such as visual inspections, are labor-intensive, time-consuming, and pose safety risks, as they can lead to accidents, while also failing to provide the real-time data needed to prevent damage. Integration of advanced sensor technologies with pavement structures has been identified as a promising solution to these challenges by allowing continuous and real-time monitoring of pavement characteristics (e.g. temperature, pressure, strain, and compaction quality).

Sensor technologies already had wide use in the field of pavement engineering, with many studies and industrial applications performing due diligence on its application. To investigate into critical performance characteristics of asphalt layers under varying environmental conditions and traffic loads, technologies such as photonic, fiber optic, RFID and piezoelectric sensors have been developed. Nevertheless, despite the progress taken, there are still major hurdles for building these sensors. Until there are solutions to problems like durability, data accuracy, cost-effectiveness and data analysis large-scale adoption is impossible. In addition, integrating sensors into asphalt environments presents significant challenges, particularly during construction when the sensors must endure the extreme heat of hot mix asphalt and the high pressure applied by rollers. Post-construction, they are further subjected to harsh conditions such as temperature fluctuations, moisture exposure, and continued mechanical stress during service life.

This research, conducted in collaboration with Heijmans, aims to evaluate the current state-of-the-art sensor technologies available for use in pavement engineering, focusing on their suitability for integration into asphalt structures. The project will assess various sensor systems in terms of their cost-effectiveness, reliability, and environmental durability, with the goal of identifying practical, innovative solutions that align with the company's objectives of improving pavement performance and sustainability. By reviewing both existing market solutions and potential future developments, this research seeks to offer Heijmans actionable recommendations for implementing sensor technologies that optimize the construction and maintenance of road infrastructure.

1.1. Problem Statement

The increasing demand for durable and high-performing road infrastructure necessitates innovative monitoring solutions for asphalt pavements. Visual inspections and core sampling used in the past take too much effort while missing important real-time information that helps us maintain roads better. The need to identify pavement problems early helps roads last longer and cuts maintenance expenses as traffic volume and environmental factors rise. Advanced sensor technologies, including fiber optic sensors, self-sensing materials, and wireless sensor networks, offer promising solutions for real-time pavement health monitoring. However, integrating these sensors into asphalt presents several challenges, including their durability under extreme environmental conditions, accuracy in long-term data collection, cost-effectiveness, and compatibility with existing construction and maintenance practices.

Despite recent advancements in sensor technology, key limitations persist, particularly regarding sensor placement optimization, data reliability, and large-scale implementation feasibility. The primary challenge is determining which sensor technology is most suitable considering factors such as sensitivity, durability, maintenance requirements, and overall cost-effectiveness. This study, conducted in collaboration with Heijmans, aims to evaluate and compare different sensor technologies for use in asphalt pavement engineering. Through a systematic literature review and multi-criteria analysis, the research will identify the most effective sensor solutions for integration into asphalt structures, addressing current industry limitations and paving the way for smart, sustainable road infrastructure.

1.2. Research Questions and Objectives

The primary objective of this study is to evaluate and identify the most suitable sensor technologies for asphalt pavement engineering, with a focus on their adaptability, durability, accuracy, and cost-effectiveness. Given the increasing demand for real-time, data-driven road monitoring solutions, this research investigates both established and emerging sensor technologies to assess their feasibility for integration into asphalt structures. Key considerations include sensor placement optimization, resilience under extreme environmental conditions, data reliability, and the ability to support predictive maintenance strategies. Furthermore, this study aims to identify common types of road damage in Dutch asphalt pavements and establish a connection between these damage mechanisms and the most effective sensor technologies for their detection. By analyzing how different sensors, such as fiber optic sensors, piezoelectric sensors, and wireless sensor networks, respond to specific types of pavement deterioration, the study provides insights into optimizing sensor selection and placement for comprehensive road health monitoring. These findings will offer practical recommendations for Heijmans and other industry stakeholders, supporting the development of smarter, more resilient road infrastructure in the Netherlands.

1.2.1. Main questions

- What are the current sensor technologies available for pavement engineering, and which of these are most suitable for use, considering their cost-effectiveness, reliability, and ability to withstand environmental conditions and operational demands?
- What are the predominant types of damage in Dutch roads, and how can sensor technologies be used to monitor and predict these damages?
- What is the optimal placement of sensors and the key operational parameters for effective sensor-based road monitoring systems?

1.2.2. Sub questions

- What are the current advancements in sensor technologies for pavement engineering, including emerging options such as self-sensing nanocomposites, carbon nanotube-embedded materials, and smartphone-based monitoring applications?
- What challenges and limitations do these sensor technologies face in terms of integration with asphalt and data accuracy?
- How do the costs and benefits of current sensor technologies compare, and what criteria can be used to assess their suitability for use in pavement engineering?

- What are the main types of damage observed in Dutch roads (e.g., rutting, cracking, raveling, unevenness)?
- How do damage types vary across the three categories of Dutch roads (motorways, provincial roads, and municipal roads)?
- What specific parameters need to be measured to predict different types of road damage effectively (e.g., stress, strain, temperature, moisture)?
- Where should sensors be placed on the road surface (e.g., side, middle, under the wheel path)?
- How frequently should measurements be taken to capture meaningful trends in road performance, and how does the age of the road after construction influence the initiation of these measurements?
- Should monitoring focus on heavy vehicles (e.g., trucks) rather than light vehicles, given their disproportionate impact on road wear and tear?

1.3. Scope of the research

This study focuses on evaluating sensor technologies for asphalt pavement monitoring, emphasizing their adaptability, durability, accuracy, and cost-effectiveness. Conducted in collaboration with Heijmans, the research aims to identify suitable sensor solutions that enhance road performance and maintenance strategies. The study examines self-sensing asphalt and composites, fiber optic sensors, and Smart Aggregates/SmartRock Sensors, assessing their ability to monitor strain, temperature, pressure, and structural integrity in asphalt pavements.

One of the key aspects of this research is linking common pavement damage types in Dutch roads to suitable sensor technologies. By understanding how different sensors respond to specific deterioration mechanisms, the study provides insights into optimizing sensor selection and deployment for effective road health monitoring.

The study also investigates optimal sensor placement and operational parameters for road monitoring. This includes determining the best locations for sensor installation (e.g., side, middle, under the wheel path) and defining measurement frequencies (weekly, monthly, seasonally) to capture meaningful trends. Additionally, it examines how the age of the road after construction influences measurement initiation and whether monitoring efforts should prioritize heavy vehicles due to their significant impact on road wear.

A (semi-)systematic literature review is conducted to analyze existing sensor technologies, their integration challenges, and their practical applications in pavement engineering. A multi-criteria decision-making (MCDM) approach using a trade-off matrix is applied to evaluate sensors based on TRL (Technology Readiness Level), cost, durability, and effectiveness. This structured evaluation ensures an objective comparison of different technologies.

While the study provides practical recommendations for implementing sensor-based road monitoring, it does not include experimental field testing, detailed economic feasibility assessments, or road repair techniques. Instead, the focus remains on assessing sensor capabilities, identifying optimal deployment strategies, and offering insights to support the development of smart, sustainable road infrastructure.

2. Literature Review

This study reviewed 13 key research papers focused on sensor technologies for asphalt pavement engineering, highlighting innovative approaches for structural health monitoring (SHM). The primary sensor technologies investigated include Fiber Bragg Grating (FBG) sensors, Distributed Optical Fiber Sensors (DOFS), piezoelectric sensors, electrochemical sensors, self-sensing materials, and wireless sensing systems. Each technology presents unique advantages and limitations in monitoring strain, stress, temperature, and crack propagation in pavements.

Optical fiber sensors, including FBG and DOFS, offer high sensitivity, durability, and resistance to environmental degradation, making them suitable for continuous pavement health monitoring. However, their high installation costs and complexity in sensor integration remain key challenges. Wireless sensors, such as SmartRock technology, enable real-time data collection and predictive maintenance, reducing the need for extensive wiring but requiring careful placement to avoid data transmission issues.

Self-sensing asphalt materials, incorporating conductive additives like carbon fibers, graphite, and carbon nanotubes (CNTs), have emerged as a promising alternative to traditional sensors. These materials enable intrinsic strain and stress monitoring without embedded sensors, enhancing long-term durability and reducing maintenance needs. However, issues such as high production costs, optimization of conductive material dispersion, and the need for large-scale validation remain barriers to widespread adoption.

Recent advancements in capacitance-based, piezoresistive, and nanocomposite-based sensing approaches show significant potential in improving asphalt pavement monitoring. These approaches leverage materials with tunable electrical properties for accurate stress and strain detection. While demonstrating high sensitivity, these technologies require further validation under real-world traffic conditions and environmental stresses.

Overall, sensor-based SHM technologies are revolutionizing pavement monitoring by enabling real-time structural assessment and predictive maintenance strategies. However, further research is necessary to optimize sensor performance, reduce implementation costs, and establish standardized methodologies for field deployment.

A detailed review of the literature can be found in Appendix A.

3. Methodology

A comprehensive methodological approach[1] was adopted for this study. First, a structured (semi-)systematic literature review (Snyder 2019) was conducted to evaluate the suitability of various sensor technologies for pavement monitoring, focusing on their functionalities, integration methods, and applications. This approach ensured a broad yet structured analysis, allowing for the identification of key trends, technological gaps, and challenges in existing solutions while maintaining flexibility in selecting relevant studies.

Based on the insights gathered, the identified technologies were categorized into three primary groups: Self-Sensing Asphalt and Composites, Fiber Optic Sensors, and Smart Aggregates/SmartRock Sensors. This categorization considered their measurement capabilities, integration feasibility, and Technology Readiness Level (TRL)[2]. Additionally, this review linked different pavement distress mechanisms (such as rutting, fatigue cracking, raveling, potholes, and unevenness) to suitable sensor technologies, providing a foundation for optimizing sensor selection in road monitoring applications.

To further analyze the practical implementation of these technologies, a multi-criteria decision-making (MCDM) approach was applied using a trade-off matrix (Ishizaka and Nemery 2013). This evaluation framework assessed sensor performance based on sensitivity, accuracy, cost, durability, environmental impact, data analysis capabilities, and TRL. By systematically comparing these criteria, the study provided an objective basis for identifying the most cost-effective and technically feasible solutions for real-time road health monitoring. This methodology offers a structured yet adaptable framework for evaluating sensor technologies in pavement engineering. By integrating a (semi-)systematic literature review, technology categorization, and multi-criteria assessment, the study contributes to advancing smart infrastructure solutions by bridging the gap between academic research and industry implementation in road monitoring systems.

[1] The approach was not limited to asphalt, also concrete and asphalt-like materials were considered

[2] Technology Readiness Level (TRL) is a standardized scale used to assess the maturity of a technology, ranging from TRL 1 (basic principles observed) to TRL 9 (fully operational in real-world conditions) Commission, E. (2014). Technology readiness levels (TRL), European Commission Brussels, Belgium**:** 4995.

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4. Categorization of Technologies Based on Their Application

To effectively evaluate the sensor technologies reviewed in the literature, they have been categorized into three primary groups based on their functionality, integration methods, and applications (Table 1). These categories are Fiber Optic Sensors, Self-Sensing Asphalt and Composites, and Smart Aggregates/SmartRock Sensors. Each group is also assessed in terms of its Technology Readiness Level (TRL), which provides insight into the maturity and field applicability of the technologies. To better understand the capabilities of each technology, a trade-off matrix was designed, considering criteria such as sensitivity, accuracy, cost, maintenance, durability, environmental impact, data analysis capabilities, and TRL level (Table 2).

A considerable emphasis is made on the measurement of stress and temperature; the prominent technologies in this field are Fiber Optic Sensors, including FBG and DOFS sensors which are optimal in terms of accuracy and flexibility. These sensors (2-2, 2-7, 2-8) are important for basic investigation of pavement deformation, thermal curling, and real-time health assessment, which is crucial for long-term infrastructure management.

Another major category is self-sensing materials and composites (2-5, 2-6, 2-10, 2-12, 2-13), which integrate conductive additives, such as carbon fibers and carbon nanotubes, directly into asphalt matrices. These innovations nullify the requirement of external sensors; and enable the precise tracking of stress, strain, and damage progression in real-time. Their compatibility with asphalt materials enhances durability, and their advanced sensing capabilities position them as promising solutions for proactive maintenance and traffic monitoring systems.

Specific technologies include Smart Aggregates (2-1) and SmartRock Sensors (2-9) that are aimed to measure the stress in limited areas as well as to provide micromechanical analysis. Smart Aggregates generate information about the asphalt at a particle level while SmartRock Sensors incorporate wireless technology to record stress, temperature fluctuations, and cracks. These systems excel in laboratory environments but require further validation under real-world conditions to address robustness concerns.

Table 1: Categorization of Technologies Based on their Applications

Literature Review	Technology	Application
2-1	Smart Aggregates (Wireless Granular Sensors)	Monitoring micromechanical behaviors in asphalt mixtures; stress-strain evolution analysis.
2-2	Optical Fiber Sensors (FBG and DOFS)	Strain, temperature, and pressure monitoring; traffic data collection; crack and void detection.
2-3	Five Key Sensor Types (FOS, Piezoelectric, Electrochemical, Wireless)	Structural health monitoring of concrete structures; real-time crack, stress, and pH monitoring.
2-4	Capacitance-Based Stress Self-Sensing	Stress monitoring in pavements; traffic load distribution analysis.
2-5	Self-Sensing Asphalt Pavements	Real-time stress, strain, and temperature monitoring; microcrack and damage detection.

Literature Review	Technology	Application
2-6	Electrical Characteristics of Self-Sensing Asphalt	Stress-strain monitoring; crack detection via electrical resistivity variations.
2-7	Fiber Optic Sensors (Thermal Curling in Concrete)	Monitoring thermal curling, strain, and tilt angles in concrete pavements.
2-8	Fiber Bragg Grating and Fabry-Perot Sensors	Long-term pavement deformation and strain monitoring; real-time pavement health assessment.
2-9	SmartRock Sensors	Monitoring stress, temperature variations, and crack propagation in asphalt layers.
2-10	MWCNTs-Epoxy Composite (Piezoresistive)	Stress and strain monitoring in pavement layers; advanced SHM.
2-11	Carbon Fiber-Based Self-Sensing Asphalt	Stress, strain, and traffic volume monitoring; vehicle weight and speed estimation.
2-12	MWCNTs-Epoxy Resin Composite	Micro-strain monitoring in asphalt pavements; deformation detection.
2-13	Self-Sensing Nanocomposites with Conductive Microspheres	High-frequency strain monitoring; micro-strain and crack detection.

Fiber Optic Sensors consist of Fiber Bragg Grating (FBG) technology and Distributed Optical Fiber Sensors (DOFS) technologies, and the Fabry-Perot-type systems as well. These sensors are very sensitive and precise for measuring strain temperature, and pressure in the pavement structures in real time. However, they are costly and demand a correct installation and adjustment to act properly. The TRL for Fiber Optic Sensors is 7 to 8, therefore they are proven in operation and require additional field use to become consolidated in large-scale applications

Self-Sensing Asphalt and Composites is concerned with the implementation of the sensing system directly in the asphalt matrix. Technologies in this category include self-sensing asphalt pavements, piezoresistive composites (e.g., those using Multi-Walled Carbon Nanotubes or carbon fibers), and self-sensing nanocomposites. These materials offer a method of monitoring of stresses, strains, and crack obstructions without applying any external sensor. These systems provide advantages in terms of more durability, less maintenance but these results show that most of the systems are in TRL level between 4 to 6 so most of them are in laboratory and prototype validation level and few of them are at field test level. Smart Aggregates and SmartRock Sensors technologies are placed in the pavement layers to determine local stress, fluctuation in temperature and corresponding development of crack patterns. Their wireless functionality and compact design make them cost-effective and easy to deploy. However, field validation is scarce especially in considered extreme environmental conditions. Smart Aggregates are at TRL 4 to 5 as these are currently assessed mostly in laboratories, and SmartRock Sensors are at TRL 9 because the technology was already proven to work in actual operation.

Table 2: Technology Categorization and MCA Table

Category	Technology	Sensitivity	Accuracy	Cost	Maintenance	Durability	Environmental Impact	Data Analysis Capabilities	TRL	Total point of MCA
Importance of Criteria		**3**	**3**	**2**	**2**	**3**	**1**	**2**	**3**	
Fiber Optic Sensors	(FBG) (DOFS)	Very High[3]	Very High	Very Expensive[4]	Minimal	Very High	Minimal[5]	Very High	7or 8	44
MCA points		(3*3)=9	(3*3)=9	(2*1)=2	(2*3)=6	(3*3)=9	(1*3)=3	(2*3)=6	(3*3)=9	
Self-Sensing Asphalt and Composites	Self-Sensing Asphalt Pavements	Very High	Normal	Expensive	Minimal	Very High	Minimal	Normal	4 or 5	37
MCA points		(3*3)=9	(3*1)=1	(2*2)=4	(2*3)=6	(3*3)=9	(1*3)=3	(2*1)=2	(3*1)=3	
Self-Sensing Asphalt and Composites	Electrical Characteristics of Self-Sensing	Very High	Normal	Expensive	Minimal	Very High	Minimal	Normal	4 or 5	37
MCA points		(3*3)=9	(3*1)=1	(2*2)=4	(2*3)=6	(3*3)=9	(1*3)=3	(2*1)=2	(3*1)=3	
Self-Sensing Asphalt and Composites	Piezoresistive Composites (MWCNTs-Epoxy)	Very High	Normal	Expensive	Minimal	Very High	Minimal	Normal	5 or 6	40
MCA points		(3*3)=9	(3*1)=1	(2*2)=4	(2*3)=6	(3*3)=9	(1*3)=3	(2*1)=2	(3*2)=6	
Self-Sensing Asphalt and Composites	Carbon Fiber-Based Self-Sensing Asphalt	Very High	Normal	Expensive	Minimal	Very High	Minimal	Normal	5 or 6	40
MCA points		(3*3)=9	(3*1)=1	(2*2)=4	(2*3)=6	(3*3)=9	(1*3)=3	(2*1)=2	(3*2)=6	
Self-Sensing Asphalt and Composites	Nanocomposites with Conductive Microspheres	Very High	Normal	Expensive	Minimal	Very High	Minimal	Normal	4 or 5	37
MCA points		(3*3)=9	(3*1)=1	(2*2)=4	(2*3)=6	(3*3)=9	(1*3)=3	(2*1)=2	(3*1)=3	
Smart Aggregates and SmartRock Sensors	Smart Aggregates (Wireless Granular Sensors)	Very High	High	Normal	Minimal	High	Minimal	High	4 or 5	43
MCA points		(3*3)=9	(3*2)=6	(2*3)=6	(2*3)=6	(3*2)=6	(1*3)=3	(2*2)=4	(3*1)=3	
Smart Aggregates and SmartRock Sensors	SmartRock Sensors	Very High	High	Normal	Minimal	Normal[6]	High	Normal	9.00	42
MCA points		(3*3)=9	(3*2)=6	(2*3)=6	(2*3)=6	(3*1)=3	(1*1)=1	(2*1)=2	(3*3)=9	

[3] Represents the highest performance or quality level e.g. FBG sensors have 1.2 pm/με strain sensitivity, 10 pm/°C temperature sensitivity, and 2 microstrain resolution, enabling precise detection of micro-deformations in asphalt.

[4] Indicates premium-priced technologies requiring significant investment. e.g. Fiber Optic system with more than 30,000€ cost.

[5] Refers to technologies that impose negligible environmental impact, e.g. Fiber Optic Sensors require minimal intervention due to their robust designs.

[6] Represents standard or baseline performance, e.g., SmartRock Sensors are fragile under the pressure of compactors.

- **Multi-Criteria Analysis (literature review)**

A Multi-Criteria Analysis (MCA) (Ishizaka and Nemery 2013) was utilized to help identify the most suitable technology. Several criteria were used to evaluate the technologies, and each technology was assigned a score against some pre-defined scales. Rating of technologies as being very high (3 points), or high (2 points) or normal (1 point) for sensitivity, accuracy, durability and data analysis capability. The scoring system was reversed for maintenance and environmental impact, assigning minimal impact/requirement (3 points), normal (2 points), and high impact/requirement (1 point). Cost of technologies was rated normal cost (3 points), expensive (2 points) and very expensive (1 point). The Technology Readiness Level (TRL) was also considered in the analysis: TRL levels 7, 8 or 9 getting 3 points, TRL levels 5 or 6 2 points, TRL levels 4 or 5 one point. The criteria used in Table 2 are not of equal importance. Based on the priorities outlined by Heijmans company, the criteria were weighted accordingly. The most important criteria were assigned a weight of 3, while the least important were assigned a weight of 1. These priority weights are reflected in the second row of Table 2, where the relative importance of each criterion for the evaluated technologies is clearly displayed. The overall performance of all technologies was the result of cumulative points across all criteria, as shown in the Table 2.

- **Cost Analysis of Sensor Technologies**

As for the cost of the reviewed sensor technologies, the overall costs implemented in such technologies differ from technologies that require high upfront investments to those that are more affordable. To provide a structured assessment, the cost impacts of the three categorized groups—Fiber Optic Sensors, Self-Sensing Asphalt and Composites, and Smart Aggregates/SmartRock Sensors—are analyzed based on their initial cost, installation complexity, maintenance requirements, and long-term savings.

- Among the most costly technologies in terms of infrastructure investment, Fiber Optic Sensors include Fiber Bragg Grating (FBG) and Distributed Optical Fiber Sensors (DOFS), whose price per unit (individual sensor, excluding the interrogator unit required for data collection) ranges from 1000 to 3000 € US. The installation of these features requires specialized equipment, their integration into the layers of pavements, and protective coverages which also add to the overall cost. However, these sensors provide long-term durability at relatively low maintenance costs to make up for the initial pricing. Also, their analysis data and monitoring function can predict the problems and avoid frequent maintenance costs and improve pavement life cycle. Hence, even though, at the initial layers of installation, the costs are relatively high, Fiber Optic Sensors have an impressive array of lifecycle cost advantages (Kara De Maeijer, Luyckx et al. 2019, Liao, Zhuang et al. 2020, Wang, Han et al. 2023).
- Self-Sensing Asphalt and Composites exhibit moderate to high cost at first usage based on the type of conductive additives incorporated. Products that contain materials like Multi-Walled Carbon Nanotubes (MWCNTs) or carbon fibers need accurate blending, and they should distribute uniformly throughout the structure that increases the complexity and cost of the installations in composites. However, these technologies do not require additional sensors that are installed outside, thus saving money in the long run. Their integration into the asphalt matrix ensures durability and long-term performance, making them cost-effective in the context of lifecycle management. Furthermore, the intrinsic sensing capabilities of these composites enable proactive maintenance, minimizing resource wastage and extending infrastructure longevity (Gulisano, Jimenez-Bermejo et al. 2024, Huang, Wang et al. 2024, Li, Hu et al. 2024, Su, Jiao et al. 2024).
- Smart Aggregates and SmartRock Sensors are useful in localized monitoring applications, which are relatively cheaper. For instance, SmartRock Sensors are available in the market at a considerably cheap price of between €125 and €155 per unit. Its application is easy; it is installed when preparing the pavement and thus lenient on the labor and equipment costs. However, their longevity and some application specific annealed properties under the actual environment need to be affirmed, and the wireless characteristic may have some data transmission issues.

Despite these limitations, Smart Aggregates and SmartRock Sensors are useful for applications where specific requirements meet some cost limitations and where this technology is a practical and inexpensive solution (Wang, Han et al. 2022, Li, Sha et al. 2023).

Table 3: Cost Analysis of Sensor Technologies

Category	Initial Cost	Installation Cost	Long-Term Savings	Cost Impact Summary
Fiber Optic Sensors	High (€1,000–€3,000)	High	High	Expensive upfront but justifiable due to longevity, minimal maintenance, and predictive maintenance benefits.
Self-Sensing Composites	Moderate to High	Moderate	High	Moderate initial cost, with significant long-term savings due to intrinsic sensing and durability.
Smart Aggregates/SmartRock	Moderate (€125–€155)	Low to Moderate	Moderate	Cost-effective for localized monitoring, with additional savings dependent on robust field validation.

To summarize the cost impacts of these technologies, a Comparative Analysis Table is provided, highlighting key parameters such as initial costs, installation requirements, long-term savings, and overall cost impact. This table serves as a visual aid to contrast the cost dynamics across the three groups, providing a clear understanding of their economic feasibility and alignment with the project's objectives.

5. Reviewing the sensor market

5.1. The Sensor Market

Sensor market globally has been growing exponentially due to increased demand of sensor in various industries with technological advancements. The market size was assessed at around USD 225.91 billion in 2023 and is projected to register USD 457.26 billion by 2032, with a CAGR of 8.3% during the forecast period. The market is propelled by the rise of sensors utilization in various industries like automotive, healthcare, industrial automation, consumer electronics, and infrastructure development (Size 2023).

Integration of sensors with the Internet of Things (IoT) is one of the key drivers for this growth. Such sensors are essential to enable IoT ecosystems to collect real time data and enable automated decision making. As this trend increases the adoption of sensors smart infrastructure, transportation systems and manufacturing which require precision and efficiency (Patil 2021).

However, sensors are playing an increasingly important role in structural health monitoring (SHM) for infrastructure and pavement engineering, among other applications, to detect stress, strain and environmental effects on roads and buildings. The emergence of self-sensing composites and of distributed fiber optic sensor (DFOS) technologies is paving the way for intelligent infrastructure providing real time monitoring and prognostics of infrastructure condition for maintenance purposes (Market 2021).

With the market also developing, there are growing opportunities for multi-functional and hybrid sensors that can incorporate many sensing capabilities within a single system. These innovations are particularly applicable in pavement engineering where durability, accuracy and ease of integration are important for long term performance. This demand emphasizes the key role that sensors play in the encouragement for innovation and sustainability in infrastructure projects (Wang, Han et al. 2023).

5.1.1. Strain Gauges

The deformation (strain) under load is measured in pavement material using strain gauges, which are widely used, offering precision and accuracy. Electrical resistance strain gauges are considered to be among the most popular types due to their sensitivity and durability. These sensors are strategically located at critical points of the pavement structure in order to acquire strain response under traffic loadings thus serving as a valid source for structural health monitoring (Measurements , HBK 2024).

The small size and fragility of these gauges means careful consideration in order to embed them into asphalt. In order to ensure durability and accuracy, strain gauges are encased in protective materials, such as epoxy or small casings, to protect them from environmental hazards — such as intrusion of water, extreme temperatures, and traffic loadings. The stress from the strain gauges can be mounted on rigid base plates or metal strips to distribute the stress more evenly, and to allow more effective strain transfer to the gauge. The embedding depth should be either to the surface, middle, or base layers depending on their measurement objective. Also, strain gauge cables are insulated and routed carefully, avoiding damage by pavement construction and operation (Mohammed, Farman et al. 2021, Liu, Cui et al. 2024).

Despite their effectiveness, putting strain gauges in asphalt doesn't come easy. Because they are small and fragile, they are susceptible to damage in asphalt mixing and compaction. By using pre-assembled packages or a robust protective casing, this can be dealt with. Standard strain gauges, however, can also be compromised by the high temperatures associated with asphalt placement (140 to 160°C), and may require high temperature-resistant strain gauges or additional insulation. In addition, strain gauges can suffer from long-term durability issues with factors such as traffic loads, thermal expansion, and environmental exposure and these need to be serving harsh conditions or maintenance-friendly sensors (Braunfelds, Senkans et al. 2022, Hassani and Dackermann 2023).

Embedment of strain gauges in asphalt is demonstrated in real-world applications. For instance, these sensors were used in road construction projects to verify asphalt behavior under traffic loads and to monitor deformation. In another instance, researchers used strain gauges to record strain responses in highways subjected to heavy vehicle traffic to improve understanding of the rutting and fatigue performance of the road (oklahoma.gov 2016, Liu, Cui et al. 2024).

Although the encapsulation, mounting and protection of strain gauges in asphalt is technically challenging, it is feasible. However, in scenarios where strain gauge size and fragility are still a limitation, alternate solutions, including fiber optic or piezoelectric sensors may provide more robust and durable options for long-term pavement monitoring. (Hassani and Dackermann 2023).

5.1.2. Strain Gauges in the market

- HBM (Hottinger Brüel & Kjær) offers a comprehensive range of strain gauges suitable for embedding in asphalt pavements to monitor stress and strain. HBM strain gauges (LY Series and XY Series) are reliable and precise solutions. Advanced features on these sensors are available for challenging pavement applications and are provided within a cost range that will allow them to be used in research as well as practical implementation (HBK 2024).
  - HBM LY Series Strain Gauges

LY Series strain gauge is a linear strain gauges used for a precise measurement of strain on flat or slightly curved surface. Grid lengths of 3 mm, 6 mm, and 12 mm make them flexible enough for differing-sized measurement requirements. This wide temperature range makes the LY series operable from -200°C to +200°C no matter what the environmental conditions. Compatible to common measurement systems with a standard resistance of 120 and 350 ohms. Additionally, the polyimide backing provides both flexibility and durability, ensuring reliable performance when embedded in asphalt pavements. These strain gauges (LY series) differ in price between approx. €95 to approx. €170 per unit, depending on size and quantity purchased. The cost may be slightly increased by specialized configurations (HBK 2024).

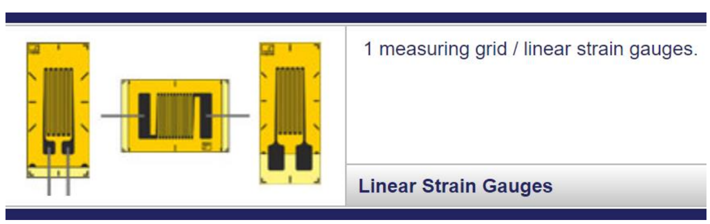

Figure 1: Three samples of LY series of Strain Gauges (HBK 2024).

  - HBM XY Series Rosette Strain Gauges

XY Series rosette strain gauges are designed to measure multi-directional strains for use in complex stress analysis in pavement monitoring. It is available in the 0°/45°/90° or 0°/60°/120° configurations to make precise strain measurements in two or three directions, respectively. The grid lengths are available in 5mm and 10mm with adaptability to different applications. These gauges work with an operating temperature range of -200°C to +200°C so you know they will perform the same, even if you're in an extreme environment. With their standard resistance of 120 and 350 ohms, and their robust design, they will work with most in use measurement equipment but they are designed to be embedded into pavements. The Strain Gauges of the XY Series are typically priced between 125€ to 285€ or thereabouts per unit, depending on the gauge configuration and technical requirements (HBK 2024).

Figure 2: Two samples of XY series of Strain Gauges (HBK 2024).

- HBM Amplifier and DAS

Amplifier is an important element in data acquisition systems especially for sensors such as strain gauges. The weak electrical signals from the sensors are then conditioned and amplified using amplifiers to achieve a strength high enough that they can be accurately recorded and analyzed. A Data Acquisition System (DAS) in turn digitizes and records these signals, turning them into a form in which they can be used for further processing, visualization, and analysis. By merging these two functions in the QuantumX series (Figure 3), HBM, a measurement technology leader, has achieved a major technical breakthrough. Through the use of this modular system, the measurement process is streamlined as an amplifier and DAS both. The table below summarizes two of their most popular models — the QuantumX MX1601B and the QuantumX MX1616B. The MX1601B is highly versatile, supporting various sensor types such as voltage and IEPE sensors, while the MX1616B is optimized for precise strain gauge measurements with advanced bridge excitation capabilities. HBM is unique in that they combine amplification and data acquisition into a single platform, increasing convenience and efficiency for various measurement applications (HBK 2024).

Table 4: HBM Amplifier Comparison

Feature	QuantumX MX1601B	QuantumX MX1616B
Number of Channels	16, electrically isolated	16, electrically isolated
Input Compatibility	Voltage (±100 mV, ±10 V, ±60 V), Current (20 mA), IEPE sensors	Strain gauges (Full, Half, Quarter-Bridge), Resistance thermometer (Pt100, Pt500, Pt1000), Potentiometric transducers
Accuracy Class	0.03 (±10 V), 0.05 (±60 V)	0.1 (Bridge Excitation - DC), 0.1 (Carrier Frequency - Linear Focus)
Signal Bandwidth	3,800 Hz (-3 dB)	DC: 3,000 Hz, Carrier Frequency: 400 Hz
TEDS Support	Yes (IEEE 1451.4)	Yes (IEEE 1451.4)
Operating Temperature	-20°C to +65°C	-20°C to +65°C
Price	6.331,75 EUR	8.787,50 EUR

Figure 3: Quantum X Amplifier and DAS

In summary, to establish a monitoring network, the total cost varies depending on the chosen configuration and components. For a minimum-cost setup, the network would consist of 16 LY or XY sensors priced at 95 EUR each (totaling 1,520 EUR), connected to a single QuantumX MX1601B module costing 6,331.75 EUR, and a suitable power supply estimated at 50 EUR. This configuration brings the total cost to approximately 7,901.75 EUR. In contrast, a maximum-cost configuration would involve sixteen LY or XY sensors priced at 285 EUR each (totaling 4,560 EUR), connected to a QuantumX MX1616B module costing 8,787.50 EUR, alongside a similar power supply estimated at 50 EUR. The total cost for this advanced setup would be approximately 13,397.50 EUR. These configurations highlight the scalability and flexibility of the QuantumX system, allowing users to tailor their network based on specific budgetary and functional requirements.

5.1.3. Fiber Optic Sensors

Pavement monitoring is carried out using advanced fiber optic sensors due to their high sensitivity, durability, and potential to deliver real-time data. Evaluating strain, temperature and stress in asphalt layers, strain and temperature are measured with two dominant types of sensors Fiber Bragg Grating (FBG) sensors and Distributed Optical Fiber Sensors (DOFS). These sensors are embedded utilizing a specialized technique which allows them to withstand harsh construction and operational conditions. Key advantages of such sensors include electromagnetic interference resistance, minimal maintenance, and ability to monitor continuously over large areas, which makes them indispensable in modern pavement health assessments.

- **Fiber Bragg Grating Sensors for Pavement Monitoring**

Fiber Bragg Grating (FBG) sensors are well suited to the stress and strain monitoring in pavement structures, for their high sensitivity, durable, and environmentally robust operation. Luna Innovations provides a range of FBG sensors tailored for structural health monitoring, including pavement applications, with diverse configurations suited for embedding in asphalt or mounting on surfaces (LUNA 2024).

The os1100 FBG (100 €) (Figure 4) sensor is a compact and lightweight option featuring a single FBG embedded in a two-meter length of polyimide-coated optical fiber. It operates effectively within a wavelength range of 1460 nm to 1620 nm and temperatures from -40°C to +120°C. With a reflectivity range of 10% to 90%, this sensor is ideal for precise strain and temperature measurements in pavement monitoring, offering versatility for embedding in various materials (LUNA 2022).

For applications requiring distributed sensing, the os1200 FBG (130 €) (Figure 4) array is a robust option. It features a six-meter polyimide-coated optical fiber with five evenly spaced FBGs, allowing for strain and temperature monitoring across multiple points. This array enables efficient installation and accurate data collection over large structural areas, making it highly suitable for monitoring the distributed stress and strain in pavements (LUNA 2022).

Figure 4: os1100, os1200 FBG Sensor (LUNA 2024).

The os3600 model (Figure 5) Intensity-based fiber optic sensors are an effective monitor for stress and strain measurements on pavements, providing precise measurements in harsh environments. The os3600 embeddable optical strain sensor from Luna Innovations is robustly designed and suitable for embedding in pavement structures. This sensor utilizes Fiber Bragg Grating (FBG) technology, inherently intensity-based, yielding precise strain data with integrated temperature compensation (LUNA 2024).

The os3600 sensor is offered in gauges of 25 cm and 100 cm and is flexible to serve particular monitoring needs. It is capable of measuring strains within the range of ±2,500 microstrain (με), which are typical for pavement deformation under load. With an operating temperature range of -40°C to +80°C, the os3600 is meant to work stable in all different climatic circumstances. Its IP67-rated water resistance protects against dust and moisture and is ideal for long-term monitoring in environments that are outdoors (LUNA 2024).

The multiplexing capability is one of the key advantages of the os3600. Multiple sensors can be connected on a single optical fiber in series by the double-ended design reducing installation complexity and allowing extensive monitoring of large paved areas. The sensor's robust construction and integrated temperature compensation further enhance its accuracy and stability, making it a reliable tool for capturing critical strain measurements essential for pavement structural health monitoring (LUNA 2024).

Figure 5: os3600 FBG Sensor (LUNA 2024).

Integration of the os3600 into pavement systems will allow engineers and researchers to obtain useful data for evaluating the performance and durability of roadways. This information will help support development of effective maintenance strategies leading to safer, longer-lasting infrastructure (LUNA 2024).

- **Distributed Fiber Optic Sensors for Pavement Monitoring**

Distributed Fiber Optic Sensors (DFOS) provide an innovative solution for monitoring stress and strain in pavements, offering high-resolution data over extensive areas. Luna Innovations' ODiSI 7000 (Figure 6) Series represents a state-of-the-art system for high-definition fiber optic sensing (HD-FOS), specifically designed for applications requiring detailed strain and temperature measurements. This technology is particularly suited for embedding within pavement structures to support comprehensive structural health monitoring (LUNA 2024).

The ODiSI 7101 offers unparalleled spatial resolution, capturing thousands of strain or temperature measurements per meter with sub-millimeter gage pitch (as fine as 0.65 mm), enabling detailed mapping of structural responses. The 8-channel sensing infrastructure allows for up to 100 m fiber length per channel making the system well suited to application over a large scale. The sensors are a lightweight, flexible, passive design, with corrosion resistant and dielectric characteristics suitable for operation in harsh environments and embedding in materials. With a strain measurement range of ±15,000 με, Ethernet connectivity for real time data acquisition, and temperature measurement capabilities, the ODiSI 7101 makes it perfect for material characterization, finite element model validation, and to detect defects (LUNA 2024).

Figure 6: ODiSI 7000 Series (LUNA 2024).

Luna Innovations suggested that the ODiSI 7101 model is commercially available at an approximate cost of about €60,000. Although the system's high degree of adaptability and performance, coupled with a low maintenance requirement, makes it desirable for some use cases, such as strain monitoring of asphalt, the system should be evaluated in terms of technical feasibility and cost to implement them. In conclusion, the ODiSI 7101 is a next generation solution for distributed sensing needs and real time, high resolution data is critical in the monitoring of materials and structures (LUNA 2024). By incorporating the DFOS technology into pavements, researchers and engineers gain uniquely powerful understanding of the structural behavior of road systems and are able to employ more effective and proactive management strategies.

- **Fabry-Pérot Interferometric Sensors for Pavement Monitoring**

Fabry-Pérot interferometric sensors offer precise and reliable measurement capabilities, making them valuable for monitoring the dynamic behavior of pavements under load. Luna Innovations' os7500 (1,900 €) (Figure 7) Optical Accelerometer, based on Fabry-Pérot (FP) technology, is a highly sensitive and durable sensor designed for detecting vibrations in challenging environments. Although primarily surface-intended, the robust design and the advanced features enable their potential embedding in the pavement structure for integrated in-pavement structural health monitoring. (LUNA 2024).

The os7500 sensor provides exceptional sensitivity, capable of accurately detecting vibrations across a frequency range of up to 350 Hz. With a Fabry–Pérot interferometric design, this device is well suited to measure minute dynamic responses in pavement materials under traffic or environmental loads. The sensor operates over a wide temperature range of -40 to 80 °C, and thanks to multiplexing capability, many sensors can be connected on a single optical fiber. This feature facilitates extensive monitoring of pavement areas with minimal installation effort (LUNA 2024).

The os7500 is specifically engineered for harsh environments, featuring a rugged design that is resistant to electromagnetic interference (EMI), lightning, and corrosion. These attributes make it suitable for long-term monitoring in outdoor and high-stress conditions and increase its durability. The os7500's primary application is structural health monitoring of civil and geotechnical structures, and thus its capability to measure vibration complements pavement monitoring requirements for understanding dynamics of road surfaces The os7500 sensor's advanced capabilities make it a reliable choice for monitoring the dynamic properties of pavements, contributing to safer and more efficient road systems (LUNA 2024).

Figure 7: os7500 Fabry-Pérot (FP) technology (LUNA 2024).

- Interrogation unit for fabry-Pérot Sensors

For use of Fabry-Pérot sensors, interrogation units are the key element, since they provide processing of optical interference patterns, and convert them into action data – strain, stress, temperature, vibration measurements, or any other measurement by creating an optical interference pattern. Without these units, the raw optical signals cannot be accurately analyzed or utilized. Luna Innovations offers advanced interrogation units specifically for use with Fabry-Pérot sensors enabling high resolution measurement that is relevant both dynamically and statically (LUNA 2024).

These units have some key traits which make them an excellent instrument for monitoring for different needs. By precisely measuring phase shifts or interference patterns, they deliver precise measurements in addition to enabling multi-sensor configurations via their multiplexing capabilities. In addition, their robust designs make them compatible with most of the available optical sensors such as Fiber Bragg Gratings (FBGs) and have housed them in ways that can withstand industrial and outdoor environments and resistance to electromagnetic interference (EMI). Notable examples include the HYPERION si255 (price range 12000€ - 54000€), which supports up to 16 channels and thousands of sensors, the FFP-I Interferometer, with its customizable spectral range, and the os7500 Optical Accelerometer, designed for dynamic vibration sensing with integrated temperature compensation. Deploying Fabry – Pérot sensors in structural health monitoring, including pavement strain and stress analysis, requires interrogation units that are critical components (LUNA 2024).

Figure 8: HYPERION si255 and HYPERION si155

5.1.4. Piezoelectric Sensors

A piezoelectric sensor is a device that make use of the piezoelectric effect to measure the mechanical parameters like strain, stress and pressure by converting the mechanical energy into electrical signals. Since these sensors have a high sensitivity and can detect dynamic changes in mechanical stress, they are widely used in structural health monitoring (SHM). There are three classical types of piezoelectric sensors regarded to their material composition, namely, the single crystal piezoelectric sensors, the ceramic piezoelectric sensors and the polymer piezoelectric sensors (Lieberzeit 2024).

Natural and synthetic quartz crystals are used to make Single Crystal Piezoelectric Sensors, which provide high precision and excellent stability. Nevertheless, due to their brittleness and fragility they are not suited to embed in pavements that would be subjected to considerable mechanical stress and environmental conditions (Lieberzeit 2024).

On the other hand, durable and robust Ceramic Piezoelectric Sensors are available, like the ones made with lead zirconate titanate (PZT). Since these sensors are highly sensitive and can tolerate the harsh conditions that exist in the pavement world, i.e., high temperatures and heavy traffic loads, some cover uncertainties. Polymer Piezoelectric Sensors, like those made from polyvinylidene fluoride (PVDF), are flexible and lightweight, which allows them to conform to pavement deformations. These sensors are especially well suited for dynamic strain monitoring and are of advantage for detecting microstrains resulting from thermal expansion or dynamic traffic loads. Further, they are also quite adaptable and resilient and so are well suited to be 'embedded' into flexible pavement systems (Taheri 2019, Lieberzeit 2024).

Among these types, ceramic and polymer piezoelectric sensors are the most suitable for pavement embedding, offering durability, flexibility, and high sensitivity to mechanical stress.

- **Ceramic piezoelectric sensors**

PCB Piezotronics offers several high-quality ceramic piezoelectric accelerometers suitable for embedding in pavement structures.

Model 356A15 (1,609 €) is a triaxial, high-sensitivity ceramic shear ICP® accelerometer for multi-axis vibration measurement. This model has a sensitivity of 100 mV/g and a frequency range of 2 to 5,000 Hz, which is suitable for methods requiring capturing of complex vibrations patterns used in pavement applications. Made from titanium, the case has a 4-pin connector, making it built to last in harsh environments. The 352C33 (523 €) has 100 mV/g sensitivity for general-purpose vibration measurements over a wide frequency range of 0.5 to 10,000 Hz. This accelerometer has a 10-32 side connector (Coaxial Jack) and is geared to go with a wide range of pavement monitoring situations. The Model 602D01 (237 €) is a low-profile, industrial-grade ceramic shear ICP® accelerometer for use in spaces where space is of the essence. With a sensitivity of 100 mV/g and a bandwidth from 0.5 to 8,000 Hz, this sensor has a side exit 2-pin connector and is useful for embedding in confined spaces within pavement structures (PCB).

Figure 9: Ceramic piezoelectric sensors

Considering the common feature of these accelerometers, they will be well suited for pavement monitoring. One of the key considerations to these sensors is their operational temperature range, usually between -55°C to 120°C. These ranges provide assurance that the sensors will maintain accuracy and are functional at the extreme temperature fluctuations that commonly exist in pavement environments, from the freezing coldness of winter to the extreme temperature experienced during the construction of hot mixed asphalt. Long-term monitoring requires temperature resilience, since the expansion and contraction of pavement materials can influence strain measurements. Additionally, side and top exits are provided as various connector options which facilitate various flexible installation configurations to support different pavement monitoring scenarios. To maintain sensor integrity and accuracy when embedding these accelerometers in pavement structures, proper installation practices are critical. Factors such as sensor orientation, protective housing, and environmental sealing play significant roles in ensuring long-term performance and reliability (PCB).

To implement a monitoring network based on ceramic piezoelectric sensors, it is essential to include Signal Conditioning Equipment and a Data Acquisition System (DAQ). For this application, the Piezotronics 482C05 (€399), a reliable signal conditioner designed specifically for ICP sensors, providing constant current excitation and signal conditioning, is a suitable choice.

A total cost of the required components to build a monitoring network with ceramic piezoelectric sensors can be obtained, given the selected configuration. With a total cost in the narrow range of 3,792 EUR for sixteen 602D01 sensors plus a Piezotronics 482C05 module of a total cost of 4,191 EUR and a suitable power supply of around 50 EUR, the network can be up and run for 4,241 EUR approximately. For a high-performance configuration, assuming sixteen 356A15 sensors at 1,609 EUR each (25,744 EUR total) and a QuantumX MX1616B module (see the previous part of this section 3-1-2-3) at 8,787.50 EUR along with a similar power supply at 50 EUR. However, this advanced setup gives a total estimated 34,581.50 EUR on the whole.

- **polymer piezoelectric sensors**

Arkema Group subsidiary Piezotech® specializes in electroactive polymers, notably the P(VDF-TrFE) fluorinated copolymers, which exhibit piezoelectric, pyroelectric, and ferroelectric properties. These materials are available in various forms, including powders, inks, and films (Figure 10), offering versatility for diverse applications. These films are generally best suited to being embedded in pavement structures due to their flexibility and ease of embedding. In particular, electroactive polymer films, such as those produced by Piezotech®, can only be embedded into pavement layers if properly encapsulated against environmental elements. Inks, while adaptable for custom sensor designs, require additional printing and protective measures for effective use in pavements. In contrast to powders, direct embedding is less practical unless the powders are processed into films or inks. Films thus represent the most efficient and practical solution for integrating polymer piezoelectric sensors into pavement systems. The films are semi-crystalline enabling high sensitivity, durability and versatility of these materials for stress and strain monitoring in pavements. The films are mechanically strong, and markedly flexible, allowing them to be integrated onto curved or uneven surfaces, ideal for placement on asphalt layers. (Arkema).

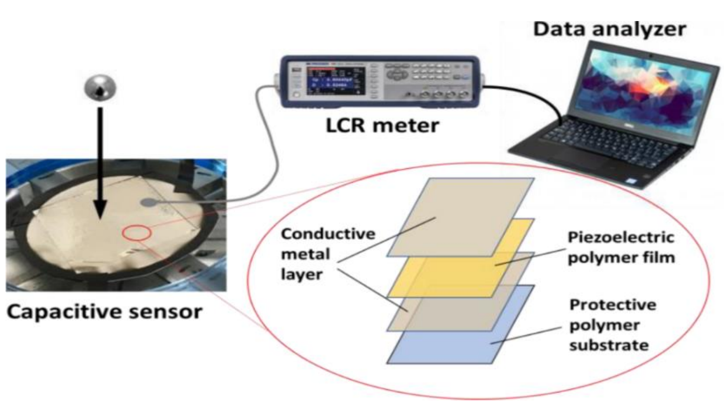

Figure 10: Film form of polymer piezoelectric sensors (Arkema).

The films are available in thicknesses of 9 µm to 1 mm, standard sizes of up to 12 cm x 12 cm, and larger-scale production is achievable through solvent casting on various substrates, allowing for customization based on specific pavement monitoring needs. These films have exceptional sensitivity to mechanical stresses with a piezoelectric coefficient (d33) ranging from -21 to -25 pC/N and a dielectric constant of 10–11 at 1 kHz. Their pyroelectric properties further enhance their ability to respond to temperature variations, adding versatility to their functionality (Arkema).

Piezotech® FC films show operational stability at high temperatures up to 130°C, thermally. For pavement applications, this is very important since surface layers can experience very significant temperature fluctuations, like high temperatures during hot mix asphalt construction. The melting point of the films is approximately 150°C and the Curie temperature is in the range of 136°C, ensuring robust performance at the extremes. The films are properly compatible to many common processing techniques such as solvent casting, screen printing and spin coating. These methods enable the configuration of custom sensors suited to specific requirements to be created (Arkema).

Applications of Piezotech® FC films include stress and strain sensors, energy harvesters that convert mechanical energy into electrical signals, and actuators for responsive systems. Their ability to endure environmental stressors, such as high temperatures and mechanical loads, coupled with their dimensional stability and chemical inertness, makes them suitable for long-term use in harsh environments like pavements. It is recommended that films be encapsulated to protect them from moisture, debris and mechanical wear in order to be effectively integrated into pavement systems. Detailed specifications and design customization should be done by collaboration with Piezotech® and used of their technical documentation. Piezotech® FC films are promising solutions to advance the durability and safety of road infrastructure through innovative pavement monitoring systems, due to their high-quality manufacturing, robust thermal and mechanical properties, and ease of integration (Arkema).

In order to monitor accurately strain and stress in asphalt using polymer piezoelectric sensors, a reliable measurement instrument should be used to process the electrical signals generated by the piezoelectric sensors. For this purpose, a cost-effective (2,418 €) solution exists in the form of the Hioki IM3523 LCR Meter, which provides precise measurement whilst maintaining affordability. Its primary functionality is for measuring the capacitance (C), inductances (L) and resistance (R) of the piezoelectric sensor components, which facilitates the detailed analysis of the electrical properties of the polymer piezoelectric sensors. This is critical for interpreting strain and stress data accurately. Hioki IM3523 LCR Meter offers measurement frequency range of D.C. - 200 KHz and high basic accuracy of ±0.05%. Reliable across a range of 5 mV to 5 V and 10 µA to 50 µA, it is suitable for a variety of sensor types and applications. At 1 kHz, the device is capable of fast measurements, capable of achieving a measurement time of 2 ms, thus allowing real-time monitoring in dynamic environments (HIOKI 2024).

5.1.5. Self-sensing Materials

- **Piezoresistive Asphalt Composites Market Challenges**

Real-time structural health monitoring (SHM) through piezoresistive asphalt composite is an innovative material capable of detecting variations in electrical resistivity under mechanical loading. However, despite these composites' promising potential for applications such as weigh-in-motion (WIM) systems and traffic detection, these composites remain largely in the research and development phase, with limited commercial availability. One of the primary challenges in incorporating conductive additives into asphalt is achieving a uniform mixture without compromising the asphalt's mechanical properties, such as strength and durability, which has necessitated continued active research in this area. However, the overall material costs including the additives such as CNTs and GNPs are quite high and therefore limit widespread adoption. Moreover, uniform dispersion of the conductive materials during manufacturing is a challenging issue for these composites regarding the consistent self-sensing properties.

Additionally, environmental factors such as temperature fluctuations, humidity, and long-term aging can affect signal stability, making it imperative to develop additives or systems resilient to such variations (Birgin, D'Alessandro et al. 2022).

Collaborative efforts with key stakeholders offer a pathway toward overcoming these challenges. Potential companies for developing these materials are companies such as SGL Carbon, a supplier of carbon microfibers (Carbon 2024). Beyond manufacturing and cost hurdles, there are several systemic limitations to the commercialization of piezoresistive asphalt composites. Industry stakeholders are uncertain due to the lack of established standards and certification protocols for use of their use in pavement monitoring. Another critical issue is scalability: these materials are difficult to produce in large quantities with the same properties. Durability and lifespan are also a matter of concern as asphalt is exposed to harsh environmental conditions (Carbon 2024, Styer, Tunstall et al. 2024).

To address such challenges, we need to see concerted efforts by researchers, manufacturers and policymakers to establish cost-effective production methods, robust data acquisition systems and standards to be implemented. Other ways to further accelerate their adoption would include pilot projects and case studies that show how they would be effective and have long-term economic benefits.

- **Self-Sensing Nanocomposites Market Challenges**

Self-sensing nanocomposites are a significant advancement in materials science incorporating conductive nanomaterials such as carbon nanotubes (CNTs). What these materials can do is monitor their structural health by sensing changes in electrical properties due to mechanical stress. Nevertheless, they are largely in the research and development stage because of several technical, economic and systemic challenges (Science 2018).

High cost of nanomaterials like CNTs and graphene is one of the major barriers for commercializing them, making the production costs extremely high. The uniform dispersion of nanomaterials in the matrix is also technically difficult, and the aggregation can diminish their sensing performance. Self-sensing properties are further complicated by environmental factors such as temperature and humidity, as well as material aging, and therefore require stabilization and compensation techniques. In addition, these composites must be extensively tested under long-term stress and harsh conditions to demonstrate mechanical and electrical durability of these composites over time. One of the remaining challenges is scaling up production from laboratory prototypes to industrial-scale manufacturing, requiring the development of efficient and scalable manufacturing (additive manufacturing, roll-to-roll) processes (Science 2018, Zhao, Zheng et al. 2020, Hassan and Tallman 2023).

Systemic challenges also impede the commercialization of self-sensing nanocomposites. The lack of standardized testing methods, certification protocol, and regulatory framework makes manufacturers and potential end users uncertain. Market acceptance is hampered by inadequate market awareness of the technology's benefits, high start-up capital costs, and difficulty in integrating the materials into existing systems. To address these problems, industry stakeholders must work together to develop clear standards, perform real-world pilot projects showing the long-term economic and operational advantages of these composites, and ensure that these standards are respected by the building owner. With the ability to overcome such challenges through innovation, collaboration and strategic investment, self-sensing nanocomposites have the potential to transform industries that need advanced monitoring and structural health (Science 2018, Hassan and Tallman 2023).

5.1.6. Wireless Sensor Technologies

- **Universal Wireless System**

For sensors that must survive in harsh construction environments in terms of strain and stress detection, sensors must be durable while reliable Wireless communication systems must also be used. One of the most versatile methods is to take advantage of a universal wireless device or platform for interaction with different sensor types. These systems typically consist of a sensor node, a microcontroller or data acquisition system (DAQ), a wireless communication module, and a power supply. Sensor node converts the sensor's output signal to a form that can be wireless transmitted and microcontroller processes the data. Then, the processed data is transmitted using such wireless communication protocols as Zigbee, LoRa, Wi-Fi or Bluetooth, according to the application requirements. There are energy supply systems, including batteries or energy harvesting processes, in remote conditions, to make sure the application always operates (Ahmed, Ali et al. 2006).

Sensor technologies vary in different output signal types produced including analog (i.e., voltage or resistance from piezoelectric or strain gauge sensors), and digital (i.e., formatted data from MEMS or fiber optic sensors). The universal wireless device must therefore accommodate both types of signals. Analog sensors need an analog-to-digital converter (ADC), while digital sensors need digital communication ports like SPI, I2C or UART. The power requirements of the sensors provide further implications. For instance, fiber optic sensors might need external power while MEMS often have low power (Čolaković, Džubur et al. 2021).

For applications on asphalt (e.g., exposed to high temperature of 150–190°C during the hot mix asphalt preparation process and under wheels of heavy equipment such as rollers, weighing 5–15 tons), environmental durability of the wireless system is critical. To operate under these conditions wireless devices are required to be rugged, heat resistant and provide functionality (Singal, Kumar et al. 2022). A universal wireless system for monitoring strain and stress in asphalt is demonstrated to be able to integrally apply multiple sensor technologies. By allowing various types of signals and supplying adequate power conditioning, such systems are made to operate in real-time and are durable with respect to environmental challenges. It optimizes the operation of embedded sensors as well as significantly contributes to the evolution of smart pavement technologies (Ahmed, Ali et al. 2006).

- To enable wireless data transmission for monitoring strain and stress in asphalt using embedded different kinds of sensors (fiber optic, Piezoelectric, MEMS-Based, capacitive, Graphene-Based) a wireless communication module is essential (Figure 11). This module connects to the output of the ODiSI 7000 Series Optical Interrogator (Figure 6), discussed in Section (3-1-2-4), and transmits the processed data to a remote system. Various wireless communication technologies can be employed based on the specific requirements of the application. For instance, LoRa is suitable for long-range, low-power transmission, Wi-Fi is ideal for real-time high-bandwidth data transmission, and 5G or LTE can be used for high-speed, wide-area networks (LUNA 2024).
- The ESP32 Wireless Communication Module by Espressif Systems is a versatile and cost-effective solution for integrating wireless capabilities into various sensor systems and IoT applications. This module supports dual wireless connectivity, including Wi-Fi (IEEE 802.11 b/g/n) operating in the 2.4 GHz band and Bluetooth, with both Bluetooth 4.2 and Bluetooth Low Energy (BLE) protocols. At up to 240 MHz clock speed, the ESP32 boasts a high-performance Tensilica LX6 dual-core microprocessor, with up to 600 DMIPS of processing power. Its 520 KB SRAM and 448 KB ROM are enough to guarantee the efficiency of it. The module supports a wide range of interfaces, including up to 36 programmable GPIOs, 12-bit SAR ADCs with up to 18 channels, two 8-bit DACs, and communication protocols such as SPI, I2C, I2S, UART, SDIO, CAN, Ethernet MAC, and PWM. These features are useful as they allow the chip to be compatible with many sensor types and smoothly embedded into many different systems. In addition to these advanced security features, the ESP32 also includes secure boot and flash encryption, and features that

secure AES, SHA-2, RSA and ECC encryption; making it a good bet for applications that need solid data protection (Espressif 2024).

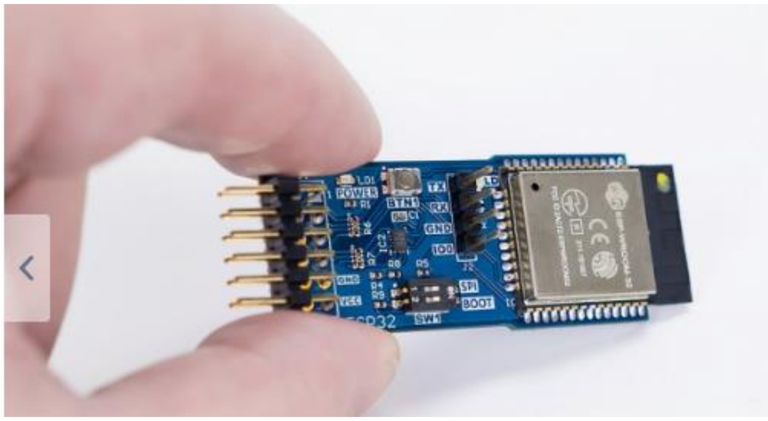

Figure 11: ESP32 Wireless Communication Module (Espressif 2024)F.

The ESP32 also exhibits a high-power efficiency. Based on a voltage range of 2.2 V to 3.6 V, the module has low power consumption operating modes, including a deep sleep mode below 10 µA and about 0.8 mA in a light sleep mode. It is compact (25 mm x 18 mm) and has operational temperature -40°C to +85°C, which qualifies it for use in challenging environments. In addition, the module has regulatory certifications such as FCC, CE, KCC, IC, MIC to meet international standards. The affordability of the ESP32 makes it even more appealing, priced from €5 — €10 per unit with or without extra features like integrated antennas or extended DRAM. It is very widely used in IoT devices, smart home systems, wearable technology, industrial automation, and wireless sensor networks, and thus a cornerstone in the development of modern, wireless-enabled systems (Espressif 2024).

In summary, to build a functional wireless system, the minimum requirements include the following components: a fiber optic sensor (approximate cost: 100 Euros); an optical signal processor like ODiSI 7101 (€60,000); a wireless communication module (10 Euros); and a power supply, which provides energy to operate the system. The cost of the power supply is estimated to be approximately 50 Euros, depending on the specific requirements and energy efficiency of the system. Combining these components, the total estimated cost for constructing a basic wireless system is approximately 60,200 Euros. This setup ensures efficient data acquisition, processing, and wireless transmission for diverse applications.

- **Phase IV Engineering Sensors**

Leap Sensors from Phase IV Engineering is a stacked, wireless sensing platform designed for IIoT applications for industries. Each transceiver node can integrate multiple sensor types—such as temperature, vibration, strain, and humidity—simultaneously facilitating comprehensive monitoring of various parameters. The sensors are built to be quick and easy to install; they come with setting parameters already built in, meaning that installation is fast. Further, the dynamic and modular nature of the system layout also facilitates easy update and additions to the existing system to address the change in monitoring demands without the need for extensive structural revisions. Three popular kinds of these sensors, along with their characteristics, are listed below. The price for all three types of sensors is €545, as listed on the Phase IV Engineering website (Phase-IV 2024).

- Wireless Strain Gauge Sensors

The Wireless Strain Gauge Sensors of Phase IV Engineering are universal and easy to use for long-term, self-powered strain measurement. These sensors are available with full, half and quarter bridge designs, and are highly accurate with the ability to calibrate remotely over the air. These models have a transmission range of up to 1,500 feet in the open air and have a battery life of 8 – 10 years at 10-minute transmit and sample intervals with standard sampling intervals. Enclosed in IP67-rated housings, they are suitable for harsh environments, operating in temperatures ranging from -40°C to 120°C. These attributes make them adaptable for various industrial applications, including potential use in pavement monitoring with proper adaptations (Phase-IV 2024).

Strain Gauge and Load Cell Transceiver Node

Figure 12: Strain Gauge and Load Cell Transceiver Node

- Wireless Axial Strain Sensors

Phase IV Engineering's wireless axial strain sensors are used to measure axial strain of structural components. These sensors are compatible with a variety of bridge configurations and strain gauge resistances and exhibit robust performance with features including over-the-air zeroing for calibration. Rugged IP68-rated enclosures provide durability of the units in extreme conditions combined with the operational temperature range from -40° C to 85° C (extending to 125° C), enabling their use under harsh conditions. The sensors have a maximum transmission range of up to 1,500 feet and an expected battery life of 5-8 years making them excellent for applications where precise axial strain monitoring is needed, such as under dynamic loads in pavements (Phase-IV 2024).

- Wireless Bending Strain Sensors

Phase IV Engineering's wireless bending strain sensors are designed to measure bending strain in structural health monitoring. These sensors support full, half, and quarter bridge configurations, offering adaptability across various applications. With IP68-rated enclosures and a temperature resistance range of -40°C to 85°C, they provide reliable performance in rugged conditions. The sensors feature a long communication range of 1,500 feet and battery life ranging from 5 to 8 years. Their ability to measure bending strain dynamically makes them suitable for monitoring deformation in pavements, provided they are integrated with protective encapsulation for asphalt-specific conditions (Phase-IV 2024).

In this system, a gateway (Figure 13) is needed to act as a central hub that collects data wirelessly from the sensors and transmits it to cloud platforms, local servers, or user interfaces, ensuring seamless integration and real-time monitoring across the network. Two popular kinds of these sensors, along with their characteristics, are listed below.

- Industrial Grade Wireless Sensor Gateway – Ethernet Connection

The Ethernet-based wireless sensor gateway by Phase IV Engineering provides robust data transmission for integrating Leap Sensors® into local area networks. A standard RJ-45 Ethernet interface connects it to allow for smooth data transfer to cloud platforms or local servers. Up to 250 sensors can be monitored through this gateway. It works in a temperature range from -20°C to 85°C and costs €295, being designed for reliable operation. While its environmental resistance is optimized for indoor use, the gateway's web-based user interface simplifies system configuration and monitoring, making it an ideal choice for infrastructure applications where Ethernet connectivity is available (Phase-IV 2024).

Ethernet / USB & Cellular Gateway Model

Figure 13: Wireless Sensor Gateway

- Industrial Grade Wireless Sensor Gateway – Cellular Connection

By using cellular networks for data transmission, the cellular wireless sensor gateway provides unparalleled flexibility in remote monitoring applications. It supports up to 250 sensors, providing reliable communication in areas without traditional network infrastructure. It also works in a temperature range of -20°C to 85°C — like the Ethernet version — for €295. The robust design continues to provide uninterrupted data flow even under demanding conditions, while the web-based user interface provides ease of deployment and management. This gateway is particularly suited for outdoor or isolated environments, such as monitoring structural health in remote regions or infrastructure projects (Phase-IV 2024).

In summary, to build a functional wireless system with Phase IV Engineering components, the minimum requirements include the following: a Leap Sensor (approximately €545 per sensor); a wireless gateway, such as the Ethernet or cellular model (priced at €295); and a power supply for both the sensors and gateway, estimated at around €50 depending on energy efficiency and operational requirements. Combining these components, the total estimated cost for constructing a basic wireless system is approximately €890 for a single sensor setup. This configuration enables efficient data acquisition, processing, and wireless transmission, making it suitable for diverse monitoring applications.

- **RVmagnetics' MicroWire-based sensors**

MicroWire-based sensors fabricated using ultra-miniaturized, glass-coated metallic wires to measure physical quantities such as temperature, pressure, and magnetic fields are provided by RVmagnetics. Without internal power and using magnetic induction for contactless communication, these passive sensors can operate. The excitation coil creates the magnetic field, while the sensing coil senses the magnetic response of the MicroWire reflecting environmental change. Running at sensing frequencies up to 10,000 times a second, the system is highly accurate and reliable, robust to strong magnetic and electric fields. Further, MicroWires are readily customizable in composition, diameter and length for specific applications. Since these sensors can be embedded in inaccessible spaces or incorporated into handheld devices for real-time or on-demand inspection, they are ideal for use in variety of industrial and infrastructure applications (RVmagnetics 2024).

To measure strain in asphalt using MicroWire-based sensors, a comprehensive system is required. The MicroWires sensors (i), which are ultra-thin, glass-coated metallic wires (diameters ranging from 20 to 70 µm), are embedded in the asphalt to monitor parameters like pressure and temperature and indirectly assess strain and stress through their magnetic properties. The system operates using a sensing head composed of two key components: an excitation coil and a sensing coil (ii). The excitation coil creates a magnetic field, and the sensing coil captures the MicroWire's magnetic response, converting it into electrical signals. For effective operation, the sensing head must be placed within 10 cm of the MicroWires. These signals are transmitted to a data processing unit, typically an ARM-based microcontroller (iii), which digitizes and processes the data for real-time analysis. The flexible design of the system allows an infinite distance between the sensing head and the microcontroller, enabling versatile configurations for continuous, efficient monitoring of asphalt conditions, critical for infrastructure management. (RVmagnetics 2024).

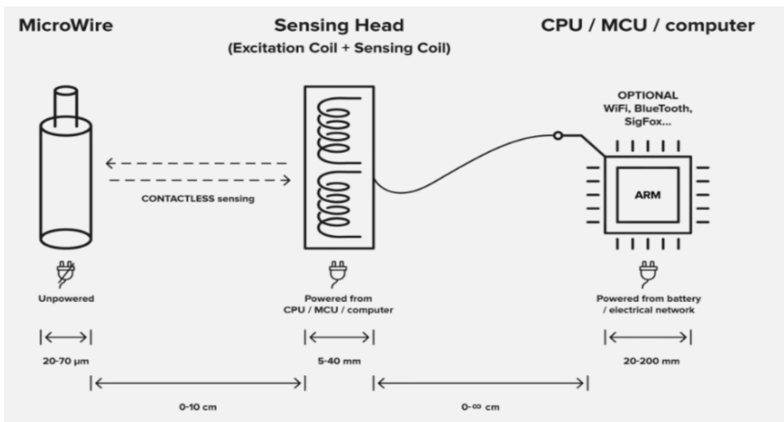

Figure 14: Operational Structure of RVmagnetics Diagram

i) RVmagnetics specializes in custom-designed MicroWire sensors tailored to specific applications. These sensors are ultra-thin, glass-coated metallic wires with diameters ranging from 3 to 70 micrometers. They are capable of directly measuring physical quantities such as temperature, pressure, and magnetic fields. They can indirectly assess parameters like stress, torsion, bending, movement, vibration, flow, electric current, and position within a magnetic field. The operating temperature range of these sensors extends from -273°C to 600°C, with a temperature measurement accuracy of 0.01°C. The sensors are designed for contactless sensing up to a distance of 10 cm and boast a lifespan exceeding 1,000 years (RVmagnetics 2024).

ii) RVmagnetics' MicroWire sensing system employs a sensing head comprising two primary components: the excitation coil and the sensing coil. The excitation coil generates a magnetic field of a few millitesla (mT), energizing the passive MicroWire sensor embedded within the material under observation. The sensing coil functions as an antenna, detecting the MicroWire's magnetic response to environmental changes, such as variations in temperature, pressure, or stress. This setup enables contactless measurement from distances up to 10 cm, even through various materials, including metals. The system operates with low power consumption, requiring only milliamperes per measurement, and supports sensing frequencies up to 50,000 times per second, facilitating real-time data acquisition (RVmagnetics 2024).

iii) MicroWire sensing system from RVmagnetics uses a data processing unit (MCU) to digitize and analysis the signals of the sensing coil. Often, the system relies on microcontrollers, such as ARM microcontrollers, famous for their efficiency and versatility. These MCUs feature integrated analog-to-digital converters (ADCs) for precise signal digitization and support various communication protocols, including USB, Bluetooth, and Wi-Fi, facilitating seamless data transmission to external devices or networks. For each application, a specific MCU is selected which is tailored to the optimal performance and integration into the sensing system (RVmagnetics 2024).

To further assess the potential use of RVmagnetics' MicroWire-based sensors for measurements of strain and stress in asphalt, an in-depth meeting was held with the company engineer, Tigran Hovhannisyan. Mr. Hovhannisyan confirmed, during the discussion, that the sensors, in theory, could be used for this purpose. Yet the product's implementation is highly dependent on customer-specific requirements because the company does particularization of its solutions to individual use cases. Mr. Hovhannisyan suggested he could not provide an exact price, but a package consisting in 25 sensors, coils and a microcontroller unit (MCU) costs some €18,000. With respect to this information, it appears that despite this high level of adaptability and readiness to a variety of applications the specific application of the technology to asphalt monitoring is at TRL 7. This rating takes into account the successful demonstration of the sensors in operational environments for other applications but requires further validation and customization for asphalt-specific need cases.

5.1.7. Sensor Technologies multi-criteria analysis (Market)

The evaluation of sensor technologies followed a Multi-Criteria Analysis (MCA) approach to systematically compare their performance. Criteria such as sensitivity, accuracy, cost, durability, environmental impact, maintenance requirements, and Technology Readiness Level (TRL) were assessed using predefined scoring scales. Since not all criteria carry equal importance, weightings were assigned based on priorities established by Heijmans. The most critical factors—sensitivity, accuracy, durability, and TRL—received a weight of 3, while cost and environmental impact were assigned weights of 2 and 1, respectively. The assigned weights ensure that the evaluation reflects the real-world trade-offs between performance and feasibility.

Each technology was rated across these criteria, with scores multiplied by their respective weights. The final cumulative score for each technology was determined by summing the weighted values, providing a structured comparison of their overall suitability. This structured evaluation allows for an objective assessment of sensor technologies, ensuring that selection decisions are based on a balance of performance, cost, and implementation feasibility

6. Monitoring and Prediction of Road Damage in Dutch Roads

6.1. Introduction

The Performance and durability of road infrastructure are important for the development of any country's economic and social development. In the Netherlands, road networks are confronted with huge traffic volumes, variations in the seasonal weather and aging materials. The factors relevant to these types of road damage include safety, efficiency and maintenance costs. The objective of this chapter is to study the main types of damages observed on Dutch roads, the variations among different road categories and methodologies to predict damages using sensor technologies.

Given the extensive road network in the Netherlands (motorways, provincial roads and municipal roads), a deep understanding of each type of damage from a monitoring and maintenance point of view is critical. Throughout its history, previous studies and reports have shown raveling, cracking, rutting and potholes as particular problems with porous asphalt pavements.

By addressing these topics, the chapter aims to provide a deeper understanding of the mechanisms driving road deterioration and to identify optimal strategies for monitoring and prediction using modern sensor technologies. The findings presented here build upon previous research, including studies on porous asphalt performance, temperature effects, and deflection measurements.

6.2. Types of Damage in Dutch Roads

Several predominant types of road damage in Dutch roads can be presented: raveling, cracking, rutting, unevenness, and potholes. These damages are also associated with specific mechanisms and environmental conditions for their development and progression (Huurman, Mo et al. 2010, Voskuilen and van de Ven 2010, Erkens, van Vliet et al. 2015).

- Raveling: The most common type of damage in Dutch roads, and in particular in porous asphalt pavements with the use on motorways is raveling. Loss of aggregate particles from the surface occurs as a result of binder degradation, traffic loading, and environmental exposure and is called aggregate abrasion. Freeze-thaw cycles, moisture infiltration and aging of binder cause raveling to occur (Voskuilen and van de Ven 2010, Erkens, van Vliet et al. 2015, Kwiatkowski, Stipanovic Oslakovic et al. 2016).

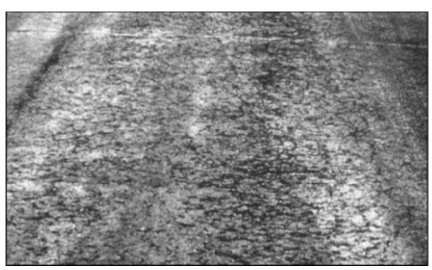

Figure 15: Raveling in asphalt pavement (Distresses)

- Cracking**:** Fatigue cracking, thermal cracking and reflective cracking are all forms that cracking of Dutch roads can take. Repeated traffic loading causes fatigue cracking: cracks that connect to go like an alligator's skin. Due to temperature fluctuations, it cracks thermally or temperature-induced (with contraction and expansion stresses). Typically, reflective cracking begins in an underlying structural layer and propagates to the surface (Distresses , Huurman, Mo et al. 2010, Kwiatkowski, Stipanovic Oslakovic et al. 2016).

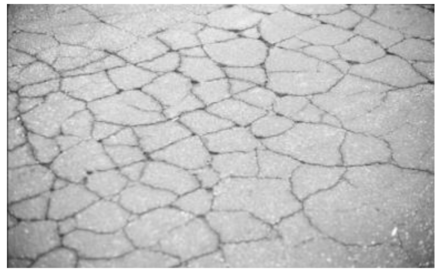

Figure 16: Fatigue (alligator) cracking in asphalt pavement (Distresses).

- Rutting: It is represented by permanent deformations in the pavement layers under traffic loads resulting to depressions in the wheel paths. In particular, this material is predominant where the material is loaded frequently, and where it is compacted and shifted as a result of repeated loading, e.g. in motorways. Factors for rutting include an insufficient pavement thickness, poor compaction, and high temperatures so that the asphalt softens (Distresses , Huurman, Mo et al. 2010).

Figure 17: Rutting in asphalt pavement (Distresses).

- Unevenness: Is the surface irregularity due to differential settlements, compaction issues or structural failures. It also affects ride quality and makes dynamic loads on vehicles accelerate further deterioration. Base, or subgrade, instability as well as moisture related damage is often associated with unevenness (Distresses , Voskuilen and van de Ven 2010).

Figure 18: Unevenness in asphalt pavement.

- Potholes: Develop as a result of localized failures, typically initiated by cracking and water infiltration. Freeze-thaw cycles exacerbate pothole formation, particularly in older pavements with weakened binder properties. Potholes pose significant hazards to road users and are costly to repair (Distresses , Huurman, Mo et al. 2010, Kwiatkowski, Stipanovic Oslakovic et al. 2016).

Figure 19: Pothole in asphalt pavement (Distresses).

6.3. Variations in Damage Types Across Road Categories

- Motorway: Motorways in the Netherlands predominantly use porous asphalt, making them highly susceptible to raveling due to binder aging, freeze-thaw cycles, and heavy traffic loads (Huurman, Mo et al. 2010, Voskuilen and van de Ven 2010). However, rutting, which is also common, does not typically originate in the porous asphalt layer. This is because porous asphalt, as a stone skeleton mixture, is highly resistant to rutting. Instead, rutting often arises from instability in the underlying asphalt layers, which are less stable and contribute to the deformation observed in wheel paths subjected to frequent heavy vehicle traffic (Distresses , Huurman, Mo et al. 2010).
- Provincial Road: Provincial roads generally experience cracking and unevenness due to moderate traffic loads and varying construction standards(Erkens, van Vliet et al. 2015, Kwiatkowski, Stipanovic Oslakovic et al. 2016). These roads often face moisture-induced stripping because of drainage issues and limited maintenance (Voskuilen and van de Ven 2010).
- Municipal Road: Municipal roads often show potholes and unevenness due to utility cuts, localized traffic stress, and lower construction quality (Distresses , Huurman, Mo et al. 2010). These roads are also prone to cracking resulting from insufficient compaction and water infiltration (Erkens, van Vliet et al. 2015, Kwiatkowski, Stipanovic Oslakovic et al. 2016).

6.4. Parameters for Predicting Road Damage

Based on the understanding of the main types of road damage and their changes for different road categories gained in Sections 4.3.1 and 4.3.2, the parameters needed for prediction and monitoring of these damages are discussed in this section (4.3.3). By measuring key parameters, stress, strain, temperature, and moisture, the road performance and the deterioration trend are forecasted through the introduction of a sensor-based system.

- Stress and Strain: Stress and strain measurements are crucial for evaluating fatigue cracking and rutting caused by repeated traffic loads (Huurman, Mo et al. 2010, Mohan 2010).
- Temperature Monitoring: Temperature variations influence thermal cracking and the rate of asphalt aging. Sensors track changes to predict damage (Voskuilen and van de Ven 2010, Kwiatkowski, Stipanovic Oslakovic et al. 2016).
- Moisture Content: Moisture affects stripping, freeze-thaw damage, and binder degradation. Monitoring water infiltration is critical (Distresses , Kwiatkowski, Stipanovic Oslakovic et al. 2016).

Stress and strain measurements are particularly important for evaluating raveling and rutting, which were identified as common damages on motorways (Section 4.3.2). High traffic volumes and heavy vehicle loads on motorways (Section 4.3.1) make these parameters critical for monitoring structural stability. For provincial roads, cracking and unevenness are the dominant issues, requiring stress, strain, and moisture monitoring to assess structural weaknesses and drainage problems. Similarly, municipal roads often suffer from potholes and unevenness, making moisture content and compaction monitoring essential for predicting damage progression and evaluating subgrade stability.

Overall, sensor-based systems targeting these parameters can enhance road infrastructure durability by enabling timely maintenance interventions. These insights guide the design of monitoring strategies for diverse road types, ensuring effective management of structural weaknesses across motorways, provincial roads, and municipal roads.

Table 5: Damage-type and Road-types Relationship

Type of Damage	Motorways	Provincial Roads	Municipal Roads	Parameters to Measure
Raveling	High occurrence due to porous asphalt and heavy traffic	Moderate occurrence due to aging and traffic loads	Less frequent but occurs in aged pavements	Stress, strain, temperature, moisture
Cracking (Fatigue, Thermal, Reflective)	Less frequent but possible in aged asphalt layers	Common, particularly reflective and fatigue cracking	Common due to utility cuts and poor compaction	Stress, strain, temperature,
Rutting	Common due to repeated heavy vehicle loads	Less frequent but possible in high-load areas	Rare due to lighter traffic loads	Stress, strain,
Unevenness	Rare but can occur due to compaction or structural failures	Moderate occurrence due to drainage and construction issues	Frequent due to poor drainage and uneven construction	moisture
Potholes	Rare, mainly caused by extreme damage in aged pavements	Rare, unless poor drainage or weak subgrades exist	Frequent due to water infiltration and freeze-thaw cycles	Moisture, drainage efficiency

6.5. Sensor Placement (Optimal Sensor Placement for Road Monitoring)

Effective road monitoring is dependent on how and where sensors are placed in the asphalt pavements. Several studies state that the sensors should be placed in areas that experience the greatest stress, such as the wheel paths, where most of the traffic loads are found (Huurman, Mo et al. 2010, Aalst, Derksen et al. 2015). The most damaged and deformed areas will occur in these areas, making them the preferred monitoring areas for structural performance. For instance, sensors embedded in the center of the wheel path capture key data related to raveling and cracking, which are primary indicators of road deterioration (Distresses , Wang, Zhong et al. 2022). On the other hand, research investigating embedded sensors within pavement layers highlights the importance of placing sensors at different depths to detect multiple stress and strain responses. For instance, strain sensors embedded at depths of 0.02 m, 0.05 m, and 0.10 m below the asphalt surface enable the determination of horizontal and vertical strain distributions. Monitoring strain distributions at various depths provides critical insights into the structural behavior of pavements, including identifying stress zones, predicting deformation, and validating pavement design models. Vertical strain measurements help assess subsurface compression and predict rutting, while horizontal strain data is essential for evaluating tensile stresses, crack propagation, and fatigue resistance. These insights are vital for optimizing pavement design and ensuring long-term performance (Liao, Zhuang et al. 2020, Wang, Han et al. 2023).

Sensors are sometimes embedded close to the top surface to simplify installation and recovery as well as effective strain measurement (Hasni, Alavi et al. 2017).

In addition, configurations such as placing sensors at the bottom of the asphalt concrete layer have been employed to monitor tensile strain and deformation, particularly under heavy traffic loads. Further studies highlight the importance of placing sensors above the crushed stone base to assess structural responses under traffic stress (Golmohammadi, Hasheminejad et al. 2024). Yet some systems suggest that distributed fiber-optic sensors be placed at 5 mm above the top, mid, and bottom layers, which would yield strain and temperature data from across several depths (Liao, Zhuang et al. 2020).

Overall, the choice of sensor placement varies with monitoring objectives of either surface deformation, subsurface strain, or dynamic loading effects. But nearly all agree that embedded sensors located within wheel paths and in structural layers proximal to the asphalt base are the regions that provide the best performance.

6.6. Operational Parameters for Prediction

- Frequency of Measurements for Road Monitoring

The frequency of sensor-based measurements plays a critical role in capturing meaningful trends in road performance. Measurement intervals are suggested to depend on monitoring system type, environmental conditions, and traffic pattern. Dynamic stress and strain measurement under heavy traffic load is recommended using such systems for continuous monitoring through real time data acquisition (Liao, Zhuang et al. 2020, Golmohammadi, Hasheminejad et al. 2024). For high traffic areas, ideal is continuous monitoring to capture rapid changes in pavement conditions due to temperature variations and repeated loading (Su, Luan et al. 2022).

Monthly or seasonal measurements are considered effective for periodic follow-up because long-term trends in road performance can be captured during temperature transitions and freeze/thaw cycles (Voskuilen and van de Ven 2010, Wang, Han et al. 2023). Such intervals allow for evaluating environmental effects, including thermal expansion, contraction, and moisture infiltration, which accelerate pavement degradation. In some of the studies, annual measurements are stressed, as in the Dutch highway monitoring programs, where extensive data of consecutive years were recorded to observe seasonal variations and aging effects (Aalst, Derksen et al. 2015).

Additionally, early-stage monitoring is highlighted as important to establish baseline data shortly after construction for initial data trending on quality of compaction initially (Liao, Zhuang et al. 2020, Su, Luan et al. 2022). Prewinter check on older pavements is advisable, to spot weaknesses and potential damage by frost and heavy loads (Voskuilen and van de Ven 2010).

In summary, the system design and objectives determine the frequency of measurements. Continuous and real-time monitoring is ideal for dynamic data, monthly or seasonal checks are for long-term trends and annual surveys are for broader performance monitoring. For newly constructed roads, immediate measurements establish baseline conditions, while older pavements benefit from pre-winter evaluations to identify vulnerabilities. The combination of periodic and continuous data acquisition ensures comprehensive road performance monitoring under varying conditions.

- Influence of Road Age on Measurement Initiation

Initiation and frequency of sensor-based measurement are related to the age of the road after construction. Studies indicate that measurements should be taken soon after construction to obtain baseline data for initial performance, compaction quality and possible structural weaknesses. Early monitoring of these defects avoids costly replacements due to poor compaction or temperature gradients that may affect pavement's long-term durability (Liao, Zhuang et al. 2020, Su, Luan et al. 2022, Wang, Han et al. 2023).

Older pavements, particularly those nearing the end of their service life (typically 11–16 years), are more prone to damage due to aging effects, such as bitumen hardening, reduced flexibility, and crack development. These pavements tend to be monitored more frequently during winter times to monitor further accelerated damage at freeze-thaw cycles and moisture infiltration. For example, porous asphalt pavements that age tend to be more susceptible to frost damage than other asphalt pavements, which suggests ongoing assessments to measure degradation (Voskuilen and van de Ven 2010).

In addition, the performance of older roads is very sensitive to seasonal variations in temperature and traffic loading, forcing the use of prewinter evaluations to identify vulnerabilities before extremely cold weather conditions unremittingly enhance structural weakness (Liao, Zhuang et al. 2020). Such seasonal assessments also provide an opportunity to evaluate trends in material degradation and performance with respect to time (Aalst, Derksen et al. 2015). Immediate measurements for newly constructed roads provide information on initial deformation from traffic loadings that can be used to adjust maintenance strategy based on information obtained during the early stages in pavement life (Wang, Zhong et al. 2022). These baseline measurements also create benchmarks against which later performance trends and unexpected stress-strain behavior are compared (Su, Luan et al. 2022).

In summary, the initiation of measurements depends heavily on the age of the pavement. Early measurements right after construction establish performance baselines, while frequent monitoring becomes critical as the pavement ages and structural vulnerabilities increase. Seasonal evaluations and pre-winter inspections further support maintaining road integrity by identifying aging-related defects.

- Focus on Heavy Vehicles for Monitoring Road Wear and Tear

Several studies found that both the impact on road wear and tear and proportionality are disproportionate with heavy vehicles such as trucks. Research indicates that heavy vehicles cause much more damage to pavements than light vehicles because of their higher axle loads and repeated stress applications. For example, heavy commercial traffic was shown to impose 1.6 times more damage than standard axle loads, emphasizing the importance of prioritizing monitoring efforts for these vehicles (Huurman, Mo et al. 2010, Golmohammadi, Hasheminejad et al. 2024).

Moreover, weigh-in-motion (WIM) technology for monitoring systems of heavy vehicles is highlighted for axles loads, and load distributions. These systems allow dynamic measurements and are therefore appropriate for measuring the cumulative effects of heavy traffic on deformation and strain. Further, they also note that slow lanes receive the largest percent of their loads and therefore disproportionately impact heavy vehicles, further justifying high monitoring at these locations (Huurman, Mo et al. 2010, Wang, Han et al. 2023).

Embedded sensors, placed usually within wheel paths, can be used to track the localized effects of heavy axle loads and to acquire strain and deformation data corresponding to the stress (Distresses , Golmohammadi, Hasheminejad et al. 2024). Optical fiber sensors have been highlighted as effective tools for continuous monitoring of heavy vehicle impacts, providing high-resolution measurements of stress and deformation patterns (Wang, Han et al. 2023). Additionally, studies utilizing real-time systems to record structural response conditions under traffic stress demonstrate the requirement for continual data collection due to dynamic loading effects resulted from the presence of heavy vehicles. Identifying fatigue damage in such systems serves to identify problems that develop faster under the repeated load cycles induced by trucks than from those inflicted by passenger cars (Hasni, Alavi et al. 2017, Su, Luan et al. 2022). Surface level wear caused by light vehicles is the dominant source, but heavy vehicles cause deeper structural damage like rutting and fatigue cracking which increases the need for frequent and detailed monitoring. Yet this focus becomes even more critical for older pavements, particularly as aged materials are not so well suited to withstanding the repeated stresses that heavy traffic places on materials (Distresses , Voskuilen and van de Ven 2010).

In summary, the literature supports prioritizing monitoring for heavy vehicles due to their disproportionate impact on road wear and tear. Technologies such as WIM systems and optical fiber sensors provide effective tools for capturing the dynamic effects of heavy axle loads, particularly in slow lanes and wheel paths, where stress concentrations are highest. Continuous and high-frequency monitoring further enables early detection of damage, ensuring the long-term performance and durability of pavements.

6.7. Linking Damage Types to Sensor Technologies

Classification of the main damage types related to different road types and determining its key characteristics and measurable parameters would be much helpful in selecting proper sensor technologies to monitor road damage (Table 6). Raveling is predominantly associated with porous asphalt (ZOAB) used as the top layer, while rutting often originates in the underlying unstable binder and base layers. These types of damage require technologies such as Fiber Optic Sensors for strain and deformation monitoring along wheel paths and Self-Sensing Asphalt for detecting stress variations. Fatigue cracking in provincial roads is frequently caused by thermal and moisture variations, compounded by insufficient bearing capacity of the road construction. Fiber Optic Sensors and Piezoelectric Sensors are highly effective stress monitoring in these conditions. For municipal roads, which are often affected by unevenness and edge cracking, Wireless Sensors provide cost-effective wide-area monitoring, while Smart Aggregates offer micromechanical insights into stress concentrations at vulnerable areas such as road edges. To address these challenges, sensor technologies can be matched to specific damage types based on their monitoring capabilities:

- Rutting and Raveling in Motorway:

These types of damage develop under high and repeated loads. Therefore, this requires deformation monitoring and aggregate loss. Fiber Optic Sensors-FBG, DOFS-suitable for long-term strain measurement and deformation within large areas but, in particular, for those along wheel paths where rutting often happens. They can provide the possibility of sensing in a fully distributed way while collecting data continuously in real time. Self-Sensing Asphalt embedded in the pavement structure monitors any variation in stresses and strains due to material displacements or losses of aggregates, making continuous health monitoring possible.

- Potholes and Fatigue Cracking in Provincial Roads:

In general, initiations or propagations of cracks due to thermal and moisture variations are possible challenges on provincial roads. In these environments, monitoring the development of cracks or variation in stress is very essential; therefore, technologies such as Fiber Optic Sensors and Piezoelectric Sensors work very effectively. The fiber optic sensor provides distributed sensing that can monitor crack propagation. Being very sensitive to stress variations, the piezoelectric sensors are suitable in order to detect crack initiation at an early stage.

- Unevenness and Edge Cracking in Municipal roads

These roads are very prone to surface irregularities and edge wear due to environmental exposure and minimal maintenance. In this respect, these roads require the following technologies: Smart Aggregates, and Wireless Sensors. Smart Aggregates provide micromechanical insight into the identification of stress concentrations at road edges where cracking usually initiates. The suitability of Wireless Sensors for municipal roads comes from the fact that they can provide wide-area monitoring with very limited infrastructure, hence making the detection of damage effective and practical.

By combining these technologies with predictive analytics and digital monitoring systems, road maintenance strategies can become more proactive, reducing long-term costs and improving road safety. The integration of sensor networks tailored to specific damage types ensures that monitoring efforts are both efficient and effective.

Table 6: Link of damage type to the Sensor Technology

Road Type	Common Damage Types	Key Characteristics	Parameters to Measure	Recommended Sensor Technologies
Motorways	Rutting, Raveling	High loads, repetitive stress, material displacement.	stress, strain, temperature, moisture,	Fiber Optic Sensors (FBG, DOFS): Measure strain and deformation over large areas. - Self-Sensing Asphalt: Monitors stress and strain in real time.
Provincial Roads	Fatigue Cracking, Unevenness	Slower traffic, higher thermal and moisture variations.	stress, strain, Moisture, compaction,	- Fiber Optic Sensors (FBG): Monitor crack propagation and depth. - Piezoelectric Sensors: Detect early-stage cracks and stress variations.
Municipal Roads	Potholes, Unevenness,	Lighter traffic, environmental exposure, lack of maintenance.	temperature, moisture	- Wireless Sensors: Offer cost-effective, wide-area monitoring in remote locations. -Smart Aggregates

7. Results and Analysis

7.1. Literature Overview

The evaluation of sensor technologies for asphalt pavement monitoring was conducted by analyzing their performance across critical parameters such as sensitivity, accuracy, cost, maintenance, durability, environmental impact, and data analysis capabilities. The results are synthesized into three key technology categories: Fiber Optic Sensors, Self-Sensing Asphalt and Composites, and Smart Aggregates/SmartRock Sensors.

7.1.1. Fiber Optic Sensors

Exemplary sensitivity and accuracy were demonstrated by Fiber Optic Sensors. Significant applications for monitoring strain, temperature, and pressure in pavement structures include technologies such as Fiber Bragg Grating (FBG) and Distributed Optical Fiber Sensors (DOFS). The analysis, however, reveals that these sensors come with high initial costs of €1,000 to €3,000 per unit, as well as the requirement for precise installation. However, the robustness and the minimal maintenance needs make them favorable for long term structural health monitoring and predictive maintenance. Advanced data processing algorithms further enhance their utility, enabling real-time monitoring and traffic classification. Fiber Optic Sensors have a Technology Readiness Level (TRL) of 8 and have been operationally validated but do not have large-scale adoption.

7.1.2. Self-Sensing Asphalt and Composites

Overall, Self-Sensing Composites and Asphalt appear to be a promising alternative for intrinsic sensing. These technologies bypass the need for external sensors by coupling conductive additives, such as carbon nanotubes and carbon fibers, directly into the asphalt matrix, which reduces maintenance requirements as well as extending the durability of the material. Such sensitivity to stress and strain enables pavement health real-time monitoring with potential use in traffic management and predictive maintenance. Though technically challenging, the uniform dispersion of materials introduces an issue; the initial cost is influenced by what type of additive is used. Results demonstrate that most of these technologies are at TRL 4–6, revealing the need for additional field validation.

7.1.3. Smart Aggregates and SmartRock Sensors

Smart Aggregates and SmartRock Sensors provide localized monitoring solutions that are both cost-effective and easy to implement. In laboratory settings like stress and temperature monitoring, SmartRock Sensors were demonstrated to be reliable at €125 to €155 per unit. The analysis demonstrates that these sensors are ideal for use in applications that require real-time data collection and targeted pavement health assessment. However, their durability under real-world environmental conditions requires further validation. Smart Aggregates are at a TRL of 4 to 5, indicating they are still in the development phase, while SmartRock Sensors, at a TRL of 9, are ready for integration into larger systems for practical use in the industry.

7.1.4. Multi-Criteria Analysis Result

The Multi-Criteria Analysis (MCA) was employed to systematically evaluate and rank the different technologies for their suitability in monitoring strain and stress in asphalt. This method allowed us to compare various technologies based on multiple factors, ensuring an objective and holistic decision-making process. The evaluation considered both quantitative and qualitative aspects, each weighted according to its relevance to Heijmans' requirements. As discussed in the methodology, the criteria were not equally weighted. Based on Heijmans’ priorities, sensitivity, accuracy, durability, and data analysis capability were considered the most critical factors, each weighted as 3 points. Relative to their effect on the overall success of the project, maintenance and some amount of environmental impact was weighed with a weight of 2 and 1 points, respectively. The cost was inversely weighted so that cheaper technologies were scored higher. Finally, the Technology Readiness Level (TRL) was used to favor technologies that are mature enough to be implemented soon.

Results of the MCA showed that Fiber Optic Sensors (FBG/DOFS) had the highest score of 44 points, which designated it as the most suitable technology. The combination of their high sensitivity, accuracy, durability, and minimal environmental impact, as well as their ability to analyse high-quality data made them the top choice. They also have a Technology Readiness Level (TRL) of 8, meaning that these sensors are extremely close to market readiness, and are scheduled to become commercially available in the near future. However, their very high cost is a drawback and will discourage their use in budget-sensitive projects.

The second-ranked technology, Wireless Granular Sensors, scored 43 points. Although it is slightly less sensitive than Fiber Optic Sensors, it offers notable advantages, such as lower costs and robust durability. Its ease of deployment and minimal maintenance requirements make it an appealing choice for practical applications. However, the technology's lower Technology Readiness Level (TRL) indicates that it is still in the laboratory phase, requiring further development before it can be widely implemented. As such, while it shows great potential, Wireless Granular Sensors may be more suitable for consideration in future projects once the technology matures.

Smart Rock Sensors collectively have 42 points ranking it the third best; they are sensitive and accurate much like the Wireless Granular sensors. However, their workability was a great disadvantage when they were used in hot mix asphalt construction environments. These sensors were discovered to be highly sensitive and easily damaged Under these conditions, these sensors do not survive the heat that comes with some 120°C when building and complications of 15-ton rollers used in construction. Although they fared well in sensitivity and accuracy, such a pre-disposition to such stiff conditions lowered their ranking dramatically.

7.2. Technology Review

7.2.1. Strain Gauges

Strain gauges have demonstrated consistent utility in structural health monitoring (SHM), specifically for measuring deformation in asphalt under dynamic loads. The analysis of the LY and XY Series strain gauges highlights both their strengths and limitations within the context of modern pavement monitoring.

- **Performance and Practical Suitability**

The LY and XY Series strain gauges distinguish themselves for their high precision and versatility, as they can operate in a wide temperature range (-200°C + 200°C). These attributes make them contenders for pavement monitoring in such climates. However, their fragility during installation poses significant challenges, especially given the high temperatures (140–160°C) and mechanical stresses associated with asphalt compaction. While their performance is commendable for targeted strain measurements, additional effort is required to ensure durability and reliability in these harsh environments.

- **Cost vs. Capability**

The cost structure of strain gauges, ranging from €95 to €285 per unit, makes them an economically viable choice for many applications. However, the analysis reveals that the additional costs for protection (e.g., epoxy encapsulation) and compatible data acquisition systems such as the HBM QuantumX amplifiers increase the total project expenditure. In spite of this, they are much cheaper than advanced sensors like fiber optic and thus ideal for budget-constrained functions.

- **Limitations in Longevity and Integration**

The susceptibility of strain gauges to damage during installation and long-term operation underlines a significant drawback. Compared to other sensor technologies, such as fiber optic and piezoelectric sensors, strain gauges require more frequent maintenance due to their limited resilience against environmental and mechanical degradation. Moreover, their dependence on precise placement, as well as their cabling, constrains their ability to scale for wide-area distributed monitoring.

- **Advantages in Targeted Applications**

Strain gauges have limitations but they're ideal for high-precision measurements in localized areas. Their compatibility with common measurement systems and relatively low deployment cost favors their use in focused research or small projects, where cost constraints are critical. Additionally, the LY and XY Series feature a broad range of configurations which can be tailored to meet project-specific needs.

- **Implications for Future Use**

However, strain gauges have a niche in a field where precise, yet targeted strain data is necessary, but broader use for comprehensive pavement monitoring is limited by durability and integration issues. Previous review encourages progress on materials for protection, as well as hybrid sensor design that may add them to a less relevant end of this SHM landscape. Moreover, the participation in infrastructure projects which tend to put a premium on cost efficiency as well as durability will continue to make strain gauges a competitive option for many applications.

7.2.2. Fiber Optic Sensors

Fiber optic sensors, particularly Fiber Bragg Grating (FBG) sensors and Distributed Fiber Optic Sensors (DFOS), have been determined to be advanced technologies for pavement monitoring. High resolution of strain and temperature with these sensors, gives a unique coverage for comprehensive structural health monitoring (SHM).

- **Performance and Capabilities**

Fiber optic sensors are unparalleled in their sensitivity and accuracy. Unlike conventional strain gauge techniques, the os1100 FBG array and the ODiSI 7101 DFOS system both provide the ability to measure strain with microstrain precision across multiple points. For applications such as distributed monitoring of large pavement areas in which detailed mapping of stress and strain responses is important, the high spatial resolution provided by DFOS (with thousands of measurements per meter measured along the sensor width) is particularly advantageous.

- **Durability and Environmental Resilience**

Another huge advantage is the durability of fiber optic sensors. With resistance to electromagnetic interference, moisture and harsh environmental conditions they are ideal for long term deployment, in pavements. Models, such as the os3600 FBG sensor (IP 67 water resistive) with temperature compensation capabilities, maintain robust performance under extreme conditions. For the same application, strain gauges are fragile and have limited lifespan.

- **Cost Considerations**

While fiber optic systems are technically superior, the high cost involved in the use of fiber is a barrier to widespread adoption. At €100 os1100 FBG sensor is a lot cheaper than strain gauges, while the ODiSI 7101 DFOS system costs approximately €60,000, which makes them far more expensive compared to strain gauges. However, building upfront costs are high, but reduced maintenance requirements and extended lifespan could pay off in long-term projects. Nevertheless, the cost disparity between fiber optic sensors and other types of strain sensors such as strain gauges and piezoelectric sensors can be decisive for applications of limited budgets.

- **Scalability and Integration**

Scaling very much onto fiber optic systems is favored and this is particularly true for any applications that need extensive monitoring. This multiplexing capability of models such as the os3600 simplifies installation and reduces complexity by allowing connection of multiple sensors with a single optical fiber. The ability to distribute several sensing elements along one fiber and build a sensing diagnostic array that enables centralized data acquisition makes fiber optic sensors especially attractive for large scale projects with distributed sensing requirements. In contrast, technologies like strain gauges require separate wiring and calibration for each sensor, limiting their scalability.

- **Comparison with Other Technologies**

Compared to strain gauges, fiber optic sensors provide higher accuracy, durability, and the capability of large area sensing with distributed sensing. But their cost and complexity make them impractical for smaller scale or budget constrained projects. While piezoelectric sensors represent a sweet spot in terms of cost and sensitivity, they do not provide multi-point measurement capability, or environmental resilience, like fiber optic sensors do.

- **Implications for Application in Pavement Monitoring**

Fiber optic sensors are considered to be a next-generation technology for SHM in the case where high-resolution, real-time data over a large area are required. Being able to interface to modern data acquisition systems, such as the ODiSI 7101, makes these probes very flexible for the needs of advanced monitoring including finite element model validation and defect detection. But their deployment should be evaluated with care against the budget of the project and the project requirements.

- **Challenges and Recommendations**

The main issues of fiber optic sensors are their high cost and specialized expertise for their installation and operation. Future developments should strive to reduce system cost and simplify deployment procedures, in order to directly enhance their adoption. They could also further demonstrate their cost effectiveness through pilot projects and long-term studies, making them more attractive for use in infrastructure monitoring.

7.2.3. Piezoelectric Sensors

In pavements, piezoelectric sensors proved to be a robust and versatile method of SHM. The use of these sensors harnesses the piezoelectric effect to convert mechanical strain into electrical signals that are suitable for dynamic stress and strain measurements under traffic and environmental loads.

- **Performance and Suitability**

Piezoelectric sensors are excellent at measurement of dynamic mechanical changes like vehicle load or thermal expansion in pavements. As an example of high sensitivity (100 mV/g), such as ceramic piezoelectric sensors (like the offerings from PCB Piezotronics) are also very sensitive to micro-level strains. Their wide frequency range (up to 10,000 Hz) suits them well for the measurement of complex vibration patterns in pavement structures. The solution of polymer piezoelectric sensors, including Piezotech® PVDF films, offers a light, flexible solution to applications requiring light, flexible solutions. The advantages of these sensors are particularly interesting for the surface to evaluate microstrains and to conform to uneven or curved surfaces, as found in asphalt layers.

- **Durability and Environmental Resilience**

Because piezoelectric sensors are inherently durable from the outset, ceramic variants in particular can withstand the high temperatures and the heavy loading that are common in pavement environments. Less robust than these analogue sensors, is the polymer piezoelectric sensor which also has great flexibility and is quite resistant to conditions. These sensors have a large operational temperature range for their applications (e.g. up to 130°C for Piezotech® films) to maintain reliability in the face of extreme temperature extremes, such as hot mix asphalt construction.

- **Cost-Effectiveness**

Piezoelectric sensors provide a cost-effective solution for dynamic pavement monitoring compared to fiber optic sensors. The price of ceramic piezoelectric sensors ranges from €237 to €1,609 per unit, and while polymer films are less costly per unit, encapsulation is necessary for prolonged use. While so affordable, you need signal conditioning equipment — for example the Piezotronics 482C05 signal conditioner (€399) — to bring the signal to the right level and beyond that. Piezoelectric sensors are better for dynamic response than strain gauges, however they are more expensive per initial cost. But in time, it can reduce these costs due to their lower maintenance requirements and longer lifespan.

- **Scalability and Integration**

Due to their scalability for small-scale and large-scale monitoring applications, piezoelectric sensors have potential as a robust and low-cost solution. The Model 356A15 ceramic sensors, designed as a localized sensor network, or the polymer-based Piezotech® films, can be embedded into a wide range of pavement configurations. The flexibility of polymer sensors allows for seamless embedding within pavement layers, while ceramic sensors can be strategically placed to monitor critical stress points. Unlike strain gauges, piezoelectric sensors exhibit a much larger measurement range, as well as greater scalability. Fiber optic sensors, on the other hand, do not have distributed sensing capabilities like fiber optic sensors, yet these sensors could monitor an extensive area with fewer installation complexities.

- **Comparison with Other Technologies**

Piezoelectric sensors strike a balance between cost and performance. Although less accurate and durable than fiber optic sensors, they do offer dynamic response and environmental factors resilience better than strain gauges. Piezoelectric sensors are cheaper and easier to deploy than fiber optical systems, but can not deliver the advantage of multi-point sensing necessary for distributed monitoring.

- **Challenges and Limitations**

Piezoelectric sensors suffer the primary challenges of sensitivity to long term environmental degradation and suitable encapsulation (particularly for polymer variants). Like ceramic, rugged sensor outputs are often not readily integrated into flexible pavement assemblies. In addition, the acquisition of dynamic strain data together with the specialized signal processing needed to interpret it can make deployment and analysis more complicated.

- **Implications for Pavement Monitoring**

Piezoelectric sensors are suitable for applications of real-time monitoring of dynamic loads and environmental changes. However, they are capable of capturing high-frequency responses and endure harsh conditions and, for that reason, are preferred for assessing the long-term performance of pavement structures. In particular, polymer sensors have potential for novel applications such as energy harvesting and microstrain detection.

7.2.4. Wireless Sensor Technologies

Modern strain and stress monitoring in pavement using wired sensor technologies can be very complex and expensive, while wireless sensor technologies are a modern approach to the problem that offers flexibility, scalability, and little dependence on complex wiring systems. In such situations, where traditional wired setups may be impractical or costly, these systems are of particular interest.

- **Performance and Capabilities**

Wireless systems for strain and stress monitoring combine sensor nodes, microcontrollers, communication modules, and power supplies to create a self-sufficient, real-time monitoring network. Technologies like the ESP32 Wireless Communication Module and Phase IV Engineering's Leap Sensors offer robust performance, with features such as extended transmission ranges, low power consumption, and compatibility with diverse sensor types. For asphalt applications, wireless systems must endure high temperatures during installation (150–190°C) and mechanical stresses during construction. The rugged designs of wireless systems, such as IP-rated enclosures for Leap Sensors, ensure durability in these harsh conditions. Additionally, their ability to integrate with analog sensors like strain gauges or piezoelectric sensors enables seamless data collection for pavement monitoring.

- **Advantages in Asphalt Applications**

Wireless sensor technologies offer several distinct advantages for strain and stress monitoring in asphalt applications. Ease of deployment is one key benefit as they eliminate the need for an expensive cabling system, resulting in a much simpler installation with significantly less risk damage during construction. In addition, these systems are highly scalable and can comfortably accommodate multiple sensor nodes over large pavement areas. For example, Phase IV Engineering supports an advanced gateway that can accommodate 250 sensors for all-inclusive monitoring of extensive infrastructure. Another huge huge advantage is the ability to do real time data acquisition through wireless protocols like Wi-Fi, LoRa and Bluetooth. The advantage of these protocols is that the immediate access to stress and strain data is invaluable for making timely pavement maintenance decision as well as analysis. Wireless systems also show great adaptability, which accommodates both analog and digital sensor outputs and makes compatible with different sensor technologies: such as strain gauge, piezoelectric sensors and fiber optic systems. This flexibility makes them an ideal candidate for relatively diverse monitoring requirements in asphalt pavements.

- **Cost Considerations**

Wireless systems offer a cost-effective alternative to wired setups, especially for large-scale deployments. For instance, a basic wireless system using ESP32 modules and strain sensors can cost as little as €5–€10 per unit for communication modules, excluding the sensor and power supply costs. Advanced systems like Phase IV's Leap Sensors are priced at approximately €545 per sensor, with gateways costing €295. These costs are competitive when considering the reduction in wiring and installation complexity. However, for applications requiring sophisticated data acquisition systems, such as integration with fiber optic sensors, the overall cost can escalate significantly. Balancing affordability with the required functionality is crucial when selecting wireless systems for asphalt monitoring.

- **Challenges and Limitations**

Despite their advantages, wireless sensor technologies face several challenges and limitations when applied to pavement monitoring. The environmental durability of these systems, however, lags behind due to their necessity to withstand high temperatures during asphalt installation of up to 150–190°C. The performance as well as the longevity of wireless modules can be affected by prolonged exposure to such extreme condition, unless extra measures of protection can be added. Second, signal reliability is a potential limitation, especially in crowded electromagnetic environments, such as an urban area or domain with many wireless networks. LoRa is a good example of a communication protocol that can help keep signal loss down by selecting the right one for different applications: LoRa, for long-range, low-power applications. Furthermore, wireless system power supply requirements constrain because many are battery-powered and must be serviced or replaced periodically. But the battery reliance can be particularly nettlesome in remote or hard-to-reach locations, where routine battery service likely won't be as readily available. Since wireless systems in asphalt monitoring applications need to be as effective and reliable as possible, it is important to address these challenges.

- **Comparison with Wired Systems**

Traditional wired setups are outperformed by wireless sensor systems with regard to flexibility, scalability, and ease of installation. Wired systems are typically more stable in signal and are easier to deploy in asphalt having its routing and difficulties with damage during construction. In contrast, wireless systems provide a practical method for dynamic and distributed monitoring, especially in remote or large-scale projects.

- **Applications in Pavement Monitoring**

In particular, wireless sensor technologies make monitoring dynamic stresses and strains in pavements very attractive. Being able to transmit real time data over long distances makes them suitable forust for roads, highways, and remote infrastructure projects. These technologies combine wireless communication modules with sensors such as piezoelectric or fiber optic systems for complete surface monitoring with insignificant disruption to pavement structures.

7.2.5. Multi-Criteria Analysis Result

The MCA results identified Fiber Optic Sensors, RVmagnetics MicroWire Sensors, and Wireless Phase IV Sensors as the top-ranked technologies for asphalt monitoring, based on their respective advantages and trade-offs (Table 7):

1) **Fiber Optic Sensors**: Fiber optic sensors gained first place in the MCA ranking due to their better sensitivity, accuracy and durability. Because of their distributed sensing capabilities and high-resolution data acquisition, they are well-suited for comprehensive pavement monitoring. However, their high cost–€60,000 for systems such as the ODiSI 7101–is an insurmountable obstacle for low-budget projects. While they are a clear choice for applications requiring precise, real-time, and large-scale monitoring, their implementation is best suited to high-priority projects or those with long-term cost-efficiency considerations.

2) **RVmagnetics MicroWire Sensors**: Placed second, RVmagnetics' MicroWire technology offers unique advantages, such as contactless measurement and extreme customization. However, the need for technology development tailored to customer requirements adds complexity and delays its readiness for immediate deployment. Additionally, while the total cost of the system (approximately €18,000) is lower than fiber optic solutions, the lack of a standardized product and its lower Technology Readiness Level (TRL 8) make it a riskier option for immediate large-scale applications.

3) **Wireless Phase IV Sensors**: Phase IV Engineering's wireless sensor technologies in third place stand out for its adaptability, its ease of deployment and comparatively low cost. The resulting systems are scalable, user-friendly and able to integrate with many sensor types and are therefore a useful solution for such mid-sized monitoring projects. The potential for battery reliance and durability of asphalt environments, however, may restrict their long-term suitability for intensive monitoring.

Fiber optic sensors were determined as the best technology based on the MCA results to monitor strain and stress in asphalt due to the outstanding accuracy, reliability, durability and distributed sensing capabilities. However, due to their high cost their adoption should be reserved for critical infrastructure projects or pilot studies for precision and reliability. Phase IV wireless sensors are a viable alternative for projects with tighter budgets or less demanding monitoring requirements, providing a cost to functionality balance. RVmagnetics' MicroWire sensors are promising, at least on paper and in test, but still require additional development and customization which makes them better suited to the future rather than near deployment. Pilot projects can be used to explore their use and validate the technology for the monitoring of asphalt.

Table 7: Comparison of Available Technology and MCA Table

	Sensitivity	Accuracy	Durability	TRL	Cost	Min cost	Maintenance	Environment Impact	Total Point of MCA
Importance of Criteria	3	3	3	3	2		2	1	
Strain Gauges	High	High	Normal	9	Normal	8K €	Normal	Minimal	37
MCA points	(3*2)=6	(3*2)=6	(3*1)=3	3*3=9	(2*3)=6		(2*2)=4	(1*3)=3	
Fiber Optic (FBG)	Very High	Very High	Very High	9	Very expensive	30K €	Minimal	Minimal	47
MCA points	(3*3)=9	(3*3)=9	(3*3)=9	3*3=9	(2*1)=2		(2*3)=6	(1*3)=3	
Fiber Optic (Fabry-Petro)	Very High	Very High	Very High	9	Very expensive	14K €	Minimal	Minimal	47
MCA points	(3*3)=9	(3*3)=9	(3*3)=9	3*3=9	(2*1)=2		(2*3)=6	(1*3)=3	
Ceramic Piezoelectric	High	High	High	9	Expensive	4.5K €	Minimal	High	38
MCA points	(3*2)=6	(3*2)=6	(3*2)=6	3*3=9	(2*2)=4		(2*3)=6	(1*1)=1	
Polymer Piezoelectric	High	High	Normal	7	Normal		Minimal	Minimal	36
MCA points	(3*2)=6	(3*2)=6	(3*1)=3	3*2=6	(2*3)=6		(2*3)=6	(1*3)=3	
Phase IV	High	High	High	9	Normal	9K €	Minimal	Minimal	42
MCA points	(3*2)=6	(3*2)=6	(3*2)=6	3*3=9	(2*3)=6		(2*3)=6	(1*3)=3	
RVmagnetics	Very High	Very High	High	7	Normal	18K €	Minimal	Minimal	45
MCA points	(3*3)=9	(3*3)=9	(3*2)=6	3*2=6	(2*3)=6		(2*3)=6	(1*3)=3	

8. Conclusion and Recommendations

- Conclusion

This study focused on the feasibility and potential of various advanced sensor technologies in asphalt pavement engineering for addressing the current demands of durable and high-performance road infrastructure. It discussed the state-of-the-art solutions in the form of fiber optic sensors, self-sensing materials, and SmartRock sensors with respect to their capabilities and limitations, and suitability for real-world applications.

Results show that fiber optic sensors provide very good accuracy, real-time monitoring of strain and temperature, and deformation to deliver critical data for proactive maintenance. However, their high initial cost and fragility remain barriers to large-scale adoption. The use of self-sensing materials, such as composites embedded with carbon nanotubes or conductive fibers, has been a promising alternative, using their intrinsic sensing capability to monitor internal stress, strain, and damage without the use of any external sensors. Those materials are cost-effective with long durability, but there is a requirement for optimization of the materials to survive under extreme environmental conditions and traffic loadings. Similarly, other wireless sensor technologies like SmartRock sensors can provide localized stress and crack monitoring with efficient data collection systems. However, further validation is essentially required in field conditions.

Overall, this study underlines the fact that no single technology meets all the requirements of ideal pavement monitoring; however, integrating its application can meet specific challenges in construction, durability, and maintenance. Moreover, the integration of these technologies into digital infrastructure management systems enables data-driven decision-making and predictive maintenance.

Overall, the study underscores that while no single technology satisfies all the criteria for optimal pavement monitoring, their combined application can address specific challenges in construction, durability, and maintenance. The research also highlighted the importance of integrating these technologies into digital infrastructure management systems to facilitate data-driven decision-making and predictive maintenance.

The Thesis represents a useful contribution to asphalt pavement engineering, as it provides a structured overview of the current status of sensor technologies and points out pathways for their development. Further work should be directed toward overcoming the identified limitations, promoting standardization, and exploring scalable implementations that will ensure a robust, sustainable, and smart road infrastructure system.

- Recommendations

1) Strategic Deployment of Fiber Optic Sensors: Due to their high sensitivity, durability, and distributed sensing, fiber optic sensors will be well-suited for critical infrastructure projects prioritized by Heijmans. The deployment of such should be done on high-traffic motorways and sections prone to significant stress and strain like wheel paths and bridge decks. Although the initial investment in fiber optic sensors may be higher, the solution is cost-efficient in the long term due to the continuous, real-time pavement health data it provides throughout the infrastructure's lifecycle.

2) Enhanced Road Maintenance through Predictive Analytics: Heijmans should leverage real-time data from fiber optic and wireless sensors to improve predictive maintenance practices. Integrating sensor data into a digital pavement management system will enable Heijmans to detect early-stage damage that can be treated and reduce repair costs while extending the life of the roads.

3) Integration of Self-Sensing Materials: Such self-sensing asphalt composites with embedded carbon nanotubes or fibers have much potential for realistic applications in terms of monitoring internal stresses and strains in real time, all without the presence of external sensors. Heijmans can implement such materials on provincial or municipal roads where economic efficiency is being prioritized. Emphasis must be directed toward locations that are prone to crack appearance and potholes, among other kinds of moisture-caused destruction.

4) Collaboration with Universities for Technology Advancement: Heijmans should, therefore, continue to strengthen their collaboration with various academic institutions such as the University of Antwerp with a view toward developing appropriate cost-effective solutions. Such collaboration will be able to use advanced laboratory platforms that simulate real conditions whereby the performance of technologies can be tested, such as fiber optic sensors. Further, the adoption of computational tools such as Finite Element Models allows for the virtual optimization of sensor integration strategies that limit dependency on expensive field trials. In these deals, Heijmans can get advanced expertise and solutions at more economical cost and also fast execution of sensor systems according to its operation requirements.

5) Education and Training: With more investment in advanced sensors and training of Heijmans employees in the field of installation, maintenance, and data analysis resulting from these advanced sensors, they can fully leverage the benefit from the use of sensor technologies. This will enhance internal expertise and build the capacity of the company to lead in innovation in asphalt pavement engineering.

6) Emphasis on Field Testing and Real-World Validation: Laboratory setups along with simulation testing generate valuable fundamental knowledge but actual field trials during application conditions remain essential for certifying sensor performance together with lifespan. Real deployment requires sensors to endure actual field conditions which include tests under various climate conditions as well as heavy traffic loads and exposure to temperature extremes and moisture. Pilot studies on high-traffic motorways and vulnerable sections should be Heijmans' priority to certify the reliability and sturdiness of sensors before large-scale deployment. This phase will help determine real-world issues, create installation techniques, and confirm the long-term viability of the technologies.

9. References

Aalst, W. v., et al. (2015). Automated Ravelling Inspection and Maintenance Planning on Porous Asphalt in the Netherlands. International Symposium Non-Destructive Testing in Civil Engineering (NDTCE), Berlin, Germany.

Ahmed, A., et al. (2006). Wired vs wireless deployment support for wireless sensor networks. TENCON 2006-2006 IEEE Region 10 Conference, IEEE.

Arkema. "Piezotech." Retrieved 1-Dec-2024, from https://piezotech.arkema.com/en/.

Birgin, H. B., et al. (2022). "Self-sensing asphalt composite with carbon microfibers for smart weigh-in-motion." Materials and Structures **55**(5): 138.

Braunfelds, J., et al. (2022). "Road pavement structural health monitoring by embedded fiber-bragg-grating-based optical sensors." Sensors **22**(12): 4581.

Carbon, S. (2024). Retrieved 03-Dec-2024, from https://www.sglcarbon.com.

Čolaković, A., et al. (2021). "Wireless communication technologies for the Internet of Things." Science, Engineering and Technology **1**(1): 1-14.

Commission, E. (2014). Technology readiness levels (TRL), European Commission Brussels, Belgium**:** 4995.

Cui, Q., et al. (2024). "Piezoresistive response of self-sensing asphalt concrete containing carbon fiber." Construction and Building Materials **426**: 136121.

Distresses, A. "Appendix A Pavement Distress Types and Causes."

Erkens, S., et al. (2015). On the need for innovation in road engineering A Dutch example. 3rd international symposium on asphalt pavements and environment, Sun City, South Africa.

Espressif (2024). ESP32 Series Datasheet Version 4.7. Espressif. https://www.espressif.com/en, Espressif. **4.7**.

GIATEC (2024). "SmartRock® Build Concrete Structures Faster, Safer, and More Economically." Retrieved 15-Nov-2024, from https://www.giatecscientific.com.

Golmohammadi, A., et al. (2024). "Performance assessment of discrete wavelet transform for de-noising of FBG sensors signals embedded in asphalt pavement." Optical Fiber Technology **82**: 103596.

Gulisano, F., et al. (2024). "Development of Self-Sensing Asphalt Pavements: Review and Perspectives." Sensors **24**(3): 792.

Hasni, H., et al. (2017). Continuous health monitoring of asphalt concrete pavements using surface-mounted battery-free wireless sensors. Bearing Capacity of Roads, Railways and Airfields, CRC Press**:** 637-643.

Hassan, H. and T. N. Tallman (2023). "Precise damage shaping in self-sensing composites using electrical impedance tomography and genetic algorithms." Structural Health Monitoring **22**(1): 372-387.

Hassani, S. and U. Dackermann (2023). "A systematic review of advanced sensor technologies for non-destructive testing and structural health monitoring." Sensors **23**(4): 2204.

HBK (2024). "Strain Gauges: Technical Information." 27-Nov-2024, from https://www.hbm.com/en/0014/strain-gauges/?product_type_no=HBM%20Strain%20Gauges:%20First%20Choice%20for%20Strain%20Measurements.

HIOKI (2024). "IM3523 - LCR MESSGERÄT." Retrieved 7-Dec-2024, from https://shop.hioki.eu/IM3523-LCR-MESSGERAET/IM3523?_gl=1*pq714y*_up*MQ..*_gs*MQ..&gclid=Cj0KCQiAgdC6BhCgARIsAPWNWH0MQ_JxlFv6ijfz_6lNkVjHvU--IoMXwRnvV87ED4HUjpG21pQNvv0aAk3-EALw_wcB.

Huang, P., et al. (2024). "Piezoresistive response of MWCNTs/Epoxy mixtures with load-sensing capability." Construction and Building Materials **438**: 137203.

Huurman, M., et al. (2010). "Porous asphalt ravelling in cold weather conditions." International Journal of Pavement Research and Technology **3**(3): 110.

Ishizaka, A. and P. Nemery (2013). Multi-criteria decision analysis: methods and software, John Wiley & Sons.

Kara De Maeijer, P., et al. (2019). "Fiber optics sensors in asphalt pavement: state-of-the-art review." Infrastructures **4**(2): 36.

Kwiatkowski, K., et al. (2016). "Potential impact of climate change on porous asphalt with a focus on winter damage." Materials and Infrastructures 2 **5**: 159-176.

Li, J., et al. (2023). "Analysis of micromechanical response to viscoelastic and plastic behaviors of asphalt mixture using a smart sensing technology." Construction and Building Materials **408**: 133782.

Li, Y., et al. (2024). "Electrical characteristics and conductivity mechanism of self-sensing asphalt concrete." Construction and Building Materials **416**: 135236.

Liao, W., et al. (2020). "Fiber optic sensors enabled monitoring of thermal curling of concrete pavement slab: Temperature, strain and inclination." Measurement **165**: 108203.

Lieberzeit, P. (2024). Piezoelectric Sensors, Springer.

Liu, Z., et al. (2024). "Sensor-Based Structural Health Monitoring of Asphalt Pavements with Semi-Rigid Bases Combining Accelerated Pavement Testing and a Falling Weight Deflectometer Test." Sensors **24**(3): 994.

LUNA (2022). "os1100 & os1200." 29-Nov-2024, from https://lunainc.com/product/os1100-os1200.

LUNA (2024). Retrieved 29-Nov-2024, from https://lunainc.com.

Market, S. C. (2021). "Global Opportunity Analysis and Industry Forecast, 2021–2030." Allied Market Research: Portland, OR, USA.

Measurements, M. "Applications of Strain Gauges in Civil Engineering.". 27-Nov-2024, from https://www.micro-measurements.com/products.

Mohammed, M., et al. (2021). State of the art of the use of strain gauges in roads. AIP Conference Proceedings, AIP Publishing.

Mohan, S. (2010). "Winter damage of porous asphalt." Delft University of Technology.

oklahoma.gov (2016). "Biography of Dr. Haleh Azari and Dr. Alaeddin Mohseni.". 27-Nov-2024, from https://www.odot.org/materials/pp/20160125_bio.pdf.

Ozturk, M. and D. D. L. Chung (2021). "Capacitance-based stress self-sensing effectiveness of a model asphalt without functional component." Construction and Building Materials **294**: 123591.

Patil, R. (2021). "The Future of Industrial Internet of Things (IIoT) after COVID19 Pandemic." International Journal of Engineering and Applied Physics **1**(3): 242-271.

PCB. "PCB Piezotronics an Amphenol Company ". Retrieved 29-Nov-2024, from https://www.pcb.com.

Phase-IV (2024). Retrieved 5-Dec-2024, from https://www.phaseivengr.com.

RVmagnetics (2024). "MicroWire sensor Data Sheet." Retrieved 5-Dec-2024, from https://www.rvmagnetics.com/data-sheet?utm_source=chatgpt.com.

RVmagnetics (2024). "Technical overview of MicroWire sensing system." Retrieved 5-Dec-2024, from https://www.rvmagnetics.com/basic-technical-overview?utm_source=chatgpt.com.

Science, A. (2018). "Self-Sensing Polymer Composites." Retrieved 3-Dec-2024, from https://www.advancedsciencenews.com/self-sensing-polymer-composites/.

Singal, A., et al. (2022). "Wireless Communication with Artificial Intelligence: Emerging Trends and Applications."

Size, F. C. M. (2023). "Share & Trends Analysis Report by Application (Plastics & Fibers, Industrial), by Product (Organic Acids, Alcohols), by Region (Asia Pacific, North America), and Segment Forecasts, 2023—2030." Grand View Research: San Francisco, CA, USA.

Snyder, H. (2019). "Literature review as a research methodology: An overview and guidelines." Journal of business research **104**: 333-339.

Styer, J., et al. (2024). "Innovations in pavement design and engineering: A 2023 sustainability review." Heliyon **10**(13).

Su, L., et al. (2024). "Ultra-low detection limit self-sensing nanocomposites with self-assembled conductive microsphere arrays for asphalt pavement health monitoring." Construction and Building Materials **427**: 136279.

Su, L., et al. (2022). "Sensing performance and optimizing encapsulation materials of a coordinated epoxy-encapsulated sensor for strain monitoring of asphalt pavement layered structures." IEEE Sensors Journal **22**(10): 9811-9823.

Taheri, S. (2019). "A review on five key sensors for monitoring of concrete structures." Construction and Building Materials **204**: 492-509.

Voskuilen, J. and M. van de Ven (2010). Winter problems with Porous Asphalt in the Netherlands. International Conference on Asphalt Pavements. Nagoya.

Wang, J., et al. (2023). "Applications of optical fiber sensor in pavement Engineering: A review." Construction and Building Materials **400**: 132713.

Wang, N., et al. (2022). "Monitoring structural health status of asphalt pavement using intelligent sensing technology." Construction and Building Materials **352**: 129025.

Wang, P., et al. (2022). "Mechanical Response Analysis of Asphalt Pavement Structure with Embedded Sensor." Coatings **12**(11): 1728.

Xin, X., et al. (2020). "Self-sensing behavior and mechanical properties of carbon nanotubes/epoxy resin composite for asphalt pavement strain monitoring." Construction and Building Materials **257**: 119404.

Zhao, Y., et al. (2020). "A self-sensing microwire/epoxy composite optimized by dual interfaces and periodical structural integrity." Composites Part B: Engineering **182**: 107606.

10.Appendices

10.1 Appendix A: Literature Review

10.1.1 Micromechanical response to viscoelastic and plastic behaviors of asphalt

The study utilized Smart Aggregates, a wireless and self-powered granular sensor, to measure inter-particle contact forces in asphalt mixtures. These sensors were embedded as point applications within the asphalt mixture during specimen preparation using a gyratory compactor (Figure 20). The Smart Aggregate integrates advanced sensing technologies, including force sensors, a tri-axial accelerometer, gyroscope, magnetometer, and temperature sensor, supported by MEMS (Micro-Electro-Mechanical Systems). This configuration allows for real-time data collection and wireless transmission, enabling seamless monitoring of micromechanical responses under various loading conditions (Li, Sha et al. 2023). However, the study does not provide specific information about the size of the Smart Aggregate sensor itself.

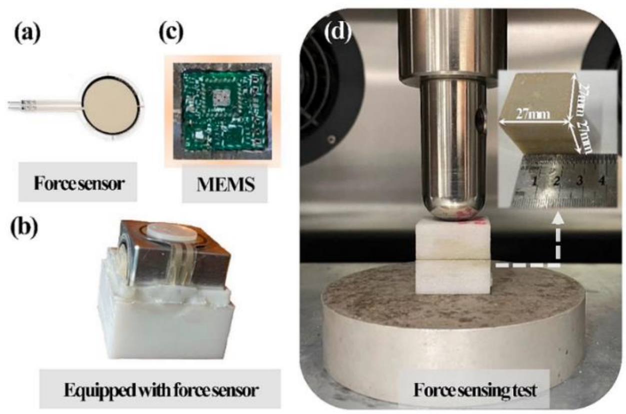

Figure 20: Smart Aggregate and its force sensing test (Li, Sha et al. 2023)

The primary role of the Smart Aggregate is to monitor micromechanical behaviors in asphalt mixtures, particularly responses to viscoelastic and plastic deformations. By detecting inter-particle contact forces, the sensor facilitates the analysis of stress and strain evolution within asphalt mixtures, thereby contributing to a deeper understanding of material performance and failure mechanisms (Li, Sha et al. 2023).

The use of Smart Aggregates offers significant advantages, including high sensitivity to strain variations, wireless functionality, and minimal maintenance requirements due to its self-powered design. The technology demonstrates strong linear correlations between measured forces and strain, highlighting its precision in capturing mechanical behaviors. Additionally, the durable 3D-printed polymer shell ensures resistance to high temperatures and mechanical stress, making the sensor suitable for challenging environments. This innovation provides granular-level insights into mechanical responses, offering a novel approach to studying pavement damage and enhancing material design (Li, Sha et al. 2023).

Despite its advantages, certain limitations have been identified. At elevated temperatures the elastically nonlinear behavior of the external shell could challenge the accuracy of measurement and necessitate calibration for temperature effects. In addition, the measured asphalt specimen may not truly reflect the overall behavior of the entire asphalt specimen as a result of the localized nature of the measurements. As an added contribution, this study points toward the need for further validation via full-scale field tests and long-term performance assessments in true-world traffic and environmental settings (Li, Sha et al. 2023).

The study addresses several critical criteria, including sensitivity, accuracy, durability, and data analysis capabilities, but does not provide explicit information on cost or environmental impact. In this research, laboratory findings demonstrate the feasibility for Smart Aggregates to monitor asphalt mixture performance; however, further research is needed to make the technology work in large-scale pavement systems and in real-world applications. These efforts would bridge existing research gaps and enhance the practical utility of this innovative sensing technology (Li, Sha et al. 2023).

10.1.2 Review of optical fiber sensor

In the paper titled "Applications of Optical Fiber Sensor in Pavement Engineering: The use of optical fiber sensors (OFS) for pavement monitoring is reviewed extensively. The paper focuses on two primary types of OFS: Fiber Bragg Grating (FBG) sensors and Distributed Optical Fiber Sensors (DOFS). Methods for embedding these sensors within asphalt pavements include slotted embedding and the use of these sensors in prefabricated asphalt specimens. Specifically, FBG sensors are embedded at discrete points, such as the bottom of pavement layers or within slotted sections (Figure 21), providing localized measurements. In contrast, DOFS are installed along lines in the pavement structure within thicknesses and can sense continuously along their lengths (Wang, Han et al. 2023)

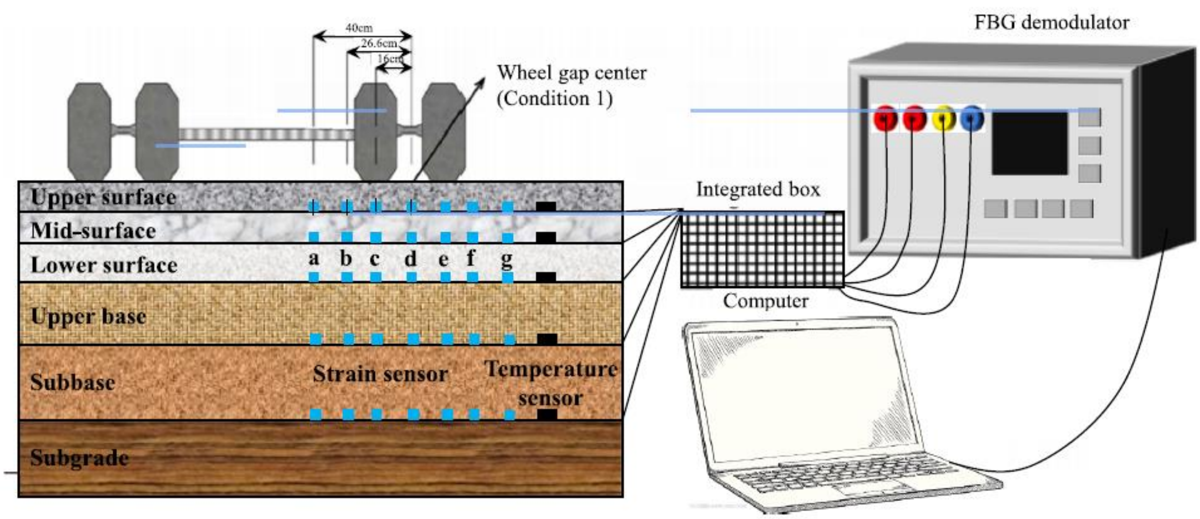

Figure 21: Assembled FBG sensor and Sensor layout in road structure (Wang, Han et al. 2023).

The role of these sensors is crucial in monitoring various parameters essential for pavement health and traffic management. FBG sensors measure strain, temperature, and pressure within pavement layers. They also facilitate weigh-in-motion (WIM) monitoring, allowing for collecting traffic data such as vehicle weight, speed, and classification. DOFS provides the capability to monitor strain and temperature over extensive areas, detect cracks, and assess the support conditions of pavement slabs (Wang, Han et al. 2023).

Key applications highlighted include real-time pavement health monitoring, traffic data collection, vehicle classification, and early detection of structural issues like cracks and voids. The advantages of using OFS in pavement engineering are notable. These include high sensitivity to strain and temperature variations, exceptional durability, resistance to corrosion and electromagnetic interference, and the ability to provide high-resolution, distributed sensing. The paper presents innovations in the form of advanced demodulation technologies for combined temperature and strain sensing, improved embedding techniques to improve sensor survival rates and measurement accuracy, and sophisticated algorithms for crack monitoring and vehicle classification (Wang, Han et al. 2023).

Despite these advantages, several limitations and challenges are associated with the technology. Optical fibers may degrade by orders of magnitude from small variations in the packaging and embedding conditions, and they need robust packaging and embedding conditions to survive installation and during operation. The separation of strain and temperature effects to provide precise measurements is complicated by its complexities and the sensors have to be calibrated. Not only are the initial costs elevated in part due to the high complexity of installation and integration processes, but these also impede efficient field deployment, given the high complexity (Wang, Han et al. 2023).

The paper addresses critical criteria related to sensor performance. The sensitivity and accuracy of OFS are high, particularly in detecting minute strain and temperature changes. Maintenance requirements are minimal owing to the long service life and robustness of the sensors. Their resistance to environmental factors and mechanical stresses help enhance durability. Sophisticated interrogation systems and algorithms enable advanced data analysis capabilities that are supported by real time monitoring and data processing. The problem is the cost aspect, which is a likely issue because of the high initial costs of deploying sensors and integrating a system. The potential for lasting pavement life and reduced need for invasive maintenance address environmental impact indirectly (Wang, Han et al. 2023).

Identified research gaps include the necessity for extensive field-scale testing under real traffic and environmental conditions to validate the long-term performance and reliability of OFS in pavement applications. There is a limited understanding of the long-term durability of these sensors when exposed to the dynamic and harsh conditions of pavement structures. Enhancement of sensor survival rates during and after installation requires optimization of embedding techniques. Additionally, there is a need to develop the ability to integrate distributed sensing data that largely handles as a source of information for maintenance strategies and pavement management systems (Wang, Han et al. 2023).

Overall, the paper encourages the significant use of optical fiber sensors to extend pavement engineering by expanding the state of the art in monitoring. Nevertheless, it points out that further development and research are needed to overcome existing shortcomings and fully exploit the advantages of this technology in real applications.

10.1.3 Review on five key sensors for monitoring of structures

The reviewed study highlights the advancements in sensor technologies developed for structural health monitoring (SHM) of concrete structures. Five key sensor types are discussed, including Fiber Optic Sensors (FOS) and Fiber Bragg Grating (FBG) sensors, piezoelectric sensors, electrochemical sensors, wireless sensors, and self-sensing concrete (Figure 22). Each sensor type is designed to address critical parameters such as temperature, humidity, pH, corrosion rate, and strain/stress/crack detection. These sensors are either embedded in concrete or mounted on the surface, enabling real-time monitoring of structural health (Taheri 2019).

Fiber optic sensors (FBG sensor in particular), utilize the variations in light signal to measure strain and other critical parameters with accuracy. Stress, deformation and the propagation of cracks can be 'detected' by piezoelectric sensors that convert mechanical energy into an electrical signal. pH levels, corrosion risks and chloride ion concentrations are monitored by electrochemical sensors. Wireless sensors facilitate the remote transmission of data, reducing installation complexities, while self-sensing concrete, incorporating conductive materials, enables intrinsic stress and strain sensing (Taheri 2019).

The applications of these sensors are significant in improving the durability and safety of concrete structures. The early detection of these processes can be achieved via real time monitoring systems which will enable timely intervention. Each sensor technology offers specific advantages. Piezoelectric sensors are known to operate reliably over wide temperature ranges with high sensitivity and low cost, whereas the fiber optic sensors possess high sensitivity and are immune to electromagnetic interference. Wireless sensors reduce maintenance needs because no extensive wiring is required, while electrochemical sensors are good corrosion monitoring tools. The integration of self-sensing materials in concrete offers an innovative approach to continuous monitoring (Taheri 2019).

However, several challenges remain in the deployment of these technologies. Fiber optic sensors require careful handling due to their fragility and high cost. Although piezoelectric sensors suffer from water solubility and temperature dependency, and electrochemical sensors from environmental drift and limited lifespan, other biosensor technologies exhibit insensitivity to chemicals. The performance of self-sensing concrete displays varies and at times demonstrate inconsistent behavior under complex stress conditions and harsh environments. in addition, wireless sensors rely on battery life and suffer from data transmission issues. (Taheri 2019).

While advancements in SHM technologies have improved sensitivity, accuracy, and durability, research gaps persist. Current tooling of these sensors under real conditions is not validated in the field, and there remain options for improving sensor survival rates through embedding optimization. Future research will include the integration of multiple sensor technologies for comprehensive monitoring and the development of robust, cost-effective systems. Filling these gaps will pave the way for furthering the potential of SHM systems to help extend the lifespan and reliability of concrete infrastructures. (Taheri 2019).

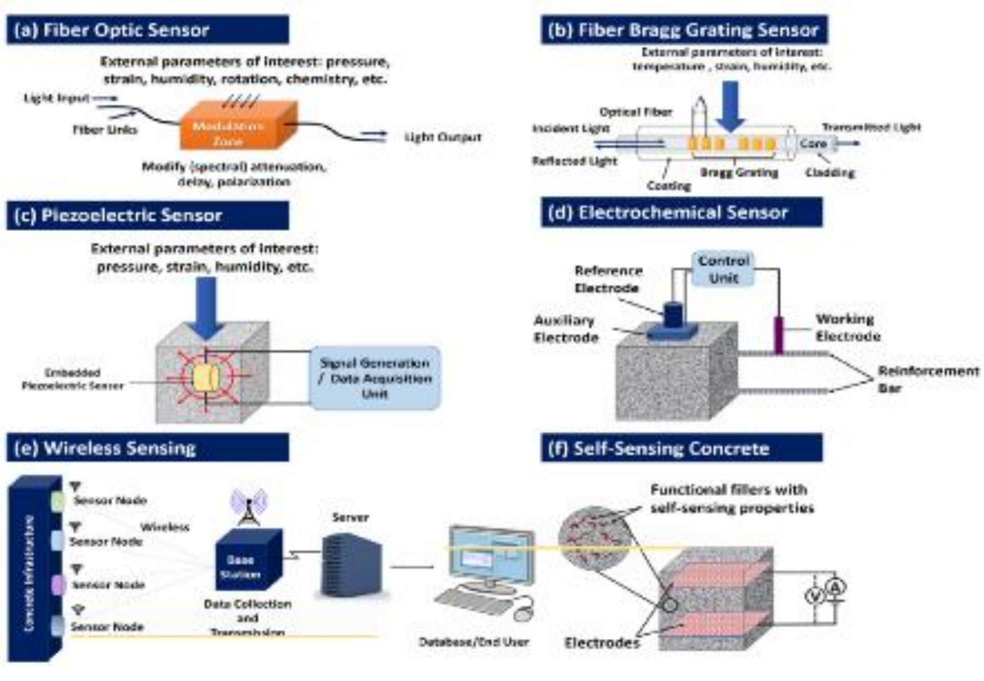

Figure 22: Illustration of a sample (a) optical fiber sensor, (b) fiber Bragg grating sensor, (c) piezoelectric sensor, (d) electrochemical sensor, (e) wireless sensor system, and (f) self-sensing concrete (Taheri 2019).

10.1.4 Capacitance-based stress self-sensing effectiveness of a model asphalt

In this study, capacitance-based self-sensing was investigated as a novel approach for stress monitoring in asphalt-like materials. A pitch-matrix composite, serving as a model for asphalt, was utilized to demonstrate the effectiveness of piezopermittivity, which refers to the change in electric permittivity under stress. The sensing system was constructed as a parallel-plate capacitor, where the composite was sandwiched between two aluminum foil electrodes (Figure 23). This design enabled distributed sensing across the material layer, providing stress measurements without requiring additional functional components (Ozturk and Chung 2021).

Figure 23: Photographs of the capacitor with pitch-matrix composite sandwiched by aluminum foil (Ozturk and Chung 2021).

The primary role of the self-sensing composite was to measure compressive stress within a range of 5–1720 Pa. While this range demonstrates high sensitivity to low stress levels, it falls significantly below the compressive stress levels typically observed in asphalt pavements, which range from 0.1 MPa to 0.8 MPa. This indicates that the composite, in its current configuration, may not be directly applicable for monitoring compressive stresses in asphalt pavement. However, its sensitivity and repeatability could make it suitable for applications in environments with lower stress levels or for modifications to expand its measurement range (Ozturk and Chung 2021).

This method holds potential for applications in stress monitoring of pavements, including load distribution analysis, traffic monitoring, and structural health assessment. Several advantages were identified, including stress sensitivity of 9.3×10^{-5} per Pa, meaning the capacitance changes by 0.000093 % for every Pascal of stress. The material used in the study is a pitch-matrix composite, scientifically akin to asphalt but not conventional asphalt. It is composed of coal tar pitch and 7.7% silica fume (by volume). Coal tar pitch, although different from petroleum-based asphalt, is used in some industrial applications, including pavement sealing. This composite provides an innovative and cost-effective alternative to traditional conductive sensing methods, eliminating the need for conductive additives and demonstrating high sensitivity and repeatability. (Ozturk and Chung 2021).

Despite its promise, certain limitations were noted. The model composite was a simplified composite of asphalt rather than conventional asphalt with more realistic aggregate proportions. Although the study was conducted under controlled laboratory conditions, immediate applicability to field situations was limited by the slight irreversibility in capacitance change observed at stress levels exceeding 1720 Pa. Future work is needed to validate this technology using asphalt mixtures and real world pavement configurations (Ozturk and Chung 2021).

Several critical performance criteria were addressed in this study. Sensitivity and accuracy were demonstrated with the system with better linear stress to capacitance correlation. The cost-effectiveness of the method was underscored by the elimination of expensive conductive additives. The durability and reliability of the system were validated through repeated stress cycles, while minimal maintenance requirements highlighted its practicality. While they did not explicitly track environmental impact, simplifying the design and decreasing material costs both help make a design more sustainable via a reduced reliance on other components (Ozturk and Chung 2021).

To enhance the applicability of capacitance-based self-sensing, further research is recommended. The integration of realistic asphalt mixtures with conventional aggregate content and the adoption of coplanar electrodes for pavement-related dimensions are suggested to facilitate practical implementation. Long-term durability assessments under real-world environmental and traffic conditions are also essential. Addressing these research gaps will help realize the full potential of this innovative stress-sensing technology in pavement engineering (Ozturk and Chung 2021).

10.1.5 Development of Self-Sensing Asphalt Pavements

To overcome the challenge of traditional pavement sensing Systems, self-sensing asphalt Pavements has emerged as an innovative solution. This technology leverages conductive asphalt mixtures composed of functional additives, such as carbon fibers, graphite powder, carbon black, steel fibers, and graphene-based nanomaterials. Intrinsic sensing capabilities are created by these additives, which produces conductive network in the asphalt matrix not requiring the presence of external embedded sensors (Figure 24). These self-sensing materials can measure variations in stress, strain, temperature, and damage by measuring changes in electrical resistivity. However, the use of these additives introduces challenges. The increased production cost due to the addition of conductive materials, such as carbon fibers or graphene-based products, can be significant. Additionally, these materials may complicate the recycling process of asphalt mixtures and increase the environmental footprint, particularly for energy-intensive materials like graphene. Therefore, careful consideration of the type and quantity of additives is essential to balance cost, recyclability, and environmental impact (MKI value) with the functional benefits of self-sensing pavements. Figure 25 provide an overview of the conceptual framework for deployment of self-sensing asphalt pavements whereby select sections of roadways are coupled with self-sensing materials to gather and convey electrical data to a centralized network for real time monitoring and analysis (Gulisano, Jimenez-Bermejo et al. 2024).

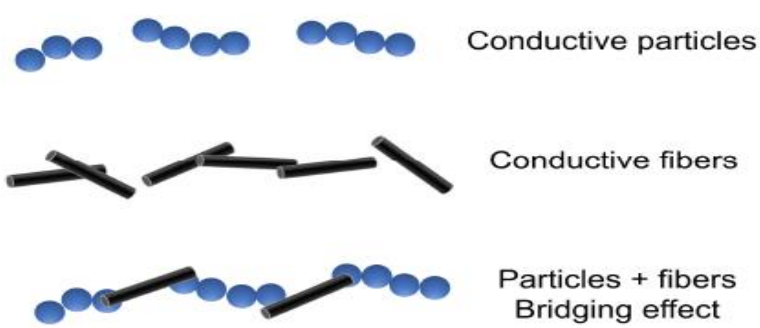

Figure 24: Combining conductive particles and fibers (Gulisano, Jimenez-Bermejo et al. 2024).

The primary role of self-sensing asphalt mixtures lies in their ability to monitor structural health, detect microcracks and damage propagation, and measure stress and strain. These materials are also utilized for traffic monitoring, weigh-in-motion (WIM) systems (which are not interested in this study), and real-time pavement condition assessments. The intrinsic sensing mechanism allows compatibility with asphalt materials and avoids durability and sensor failure. Finally, integration of these materials with advanced technologies, including Digital Twins and Vehicle-to-Infrastructure communication systems, is a major breakthrough in transportation infrastructure (Gulisano, Jimenez-Bermejo et al. 2024)

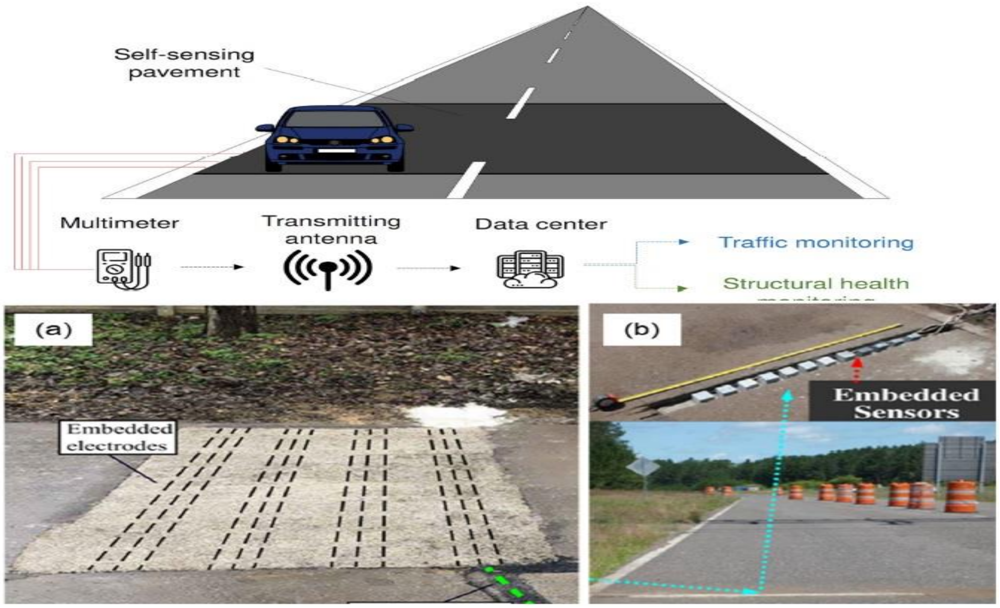

Figure 25: Self-sensing road pavement and Self-sensing configurations: (a) bulk and (b) array arrangements

The advantages of self-sensing asphalt pavements are noteworthy. The elimination of embedded sensors reduces installation complexity and enhances the long-term reliability of the system. Pavement stress and damage can be accurately and sensitively identified enabling early detection and under predictive maintenance. Additionally, these materials are suitable with asphalt and yet as for getting mechanical and environmental durability the structure of the pavement remains unchanged. Nevertheless, there remain challenges including determining the appropriate concentration and type of conductive additives to optimize sensing efficiency with mechanical performance. Technical hurdles exist of uniform dispersion of nanomaterials into the asphalt matrix and further research is required to validate the long term durability of these materials under real world conditions (Gulisano, Jimenez-Bermejo et al. 2024).

This technology addresses several critical performance criteria. Using precise calibration of electrical responses to stress and strain, high sensitivity and accuracy are achieved. The integration of sensing into the asphalt itself minimizes maintenance requirements and the compatibility of the conductive network with the host material improves durability. Initially, costs of the choice and amounts of conductive additives can influence costs, but the costs associated with reduced maintenance and extended pavement life make such a system beneficial. Moreover, it enables real-time monitoring and interpretation of electrical signals to facilitate decision making in the context of pavement management system. Through predictive maintenance, this technology mitigates the environmental impact of this technology, therefore reducing material waste and extending pavement life (Gulisano, Jimenez-Bermejo et al. 2024).

Despite these advancements, several research gaps persist. Such validation field scale under real world traffic and environmental conditions is still lacking and the methodologies to produce and validate self-sensing asphalt mixtures haven't been standardized. Further improvement of both the sensing performance and mechanical properties is achieved by optimization of additive content and dispersion techniques. Additionally, the practical benefits that can be derived from this technology require the integration of self-sensing data with large scale pavement management systems. These gaps will be addressed to enable widespread implementation of self-sensing asphalt pavements, a way of tackling the pavement monitoring and maintenance (Gulisano, Jimenez-Bermejo et al. 2024).

10.1.6 Electrical characteristics and conductivity mechanism of self-sensing asphalt

The development of self-sensing asphalt concrete has introduced an innovative approach to monitoring the structural health of pavement systems. Incorporation of conductive additives such as graphite and steel fibers (Figure 26) into asphalt concrete to enable self-sensing capabilities is the focus of this study. By forming a conductive particle chain within the asphalt matrix, graphite increases conductivity, and by bridging the asphalt matrix with a conductive network, steel fibers increase conductivity. The additives are dispersed uniformly throughout the asphalt mixture and form a continuous conductive network in the material to monitoring internal stress, strain and structural damage by means of change in the material's electrical resistivity (Li, Hu et al. 2024).

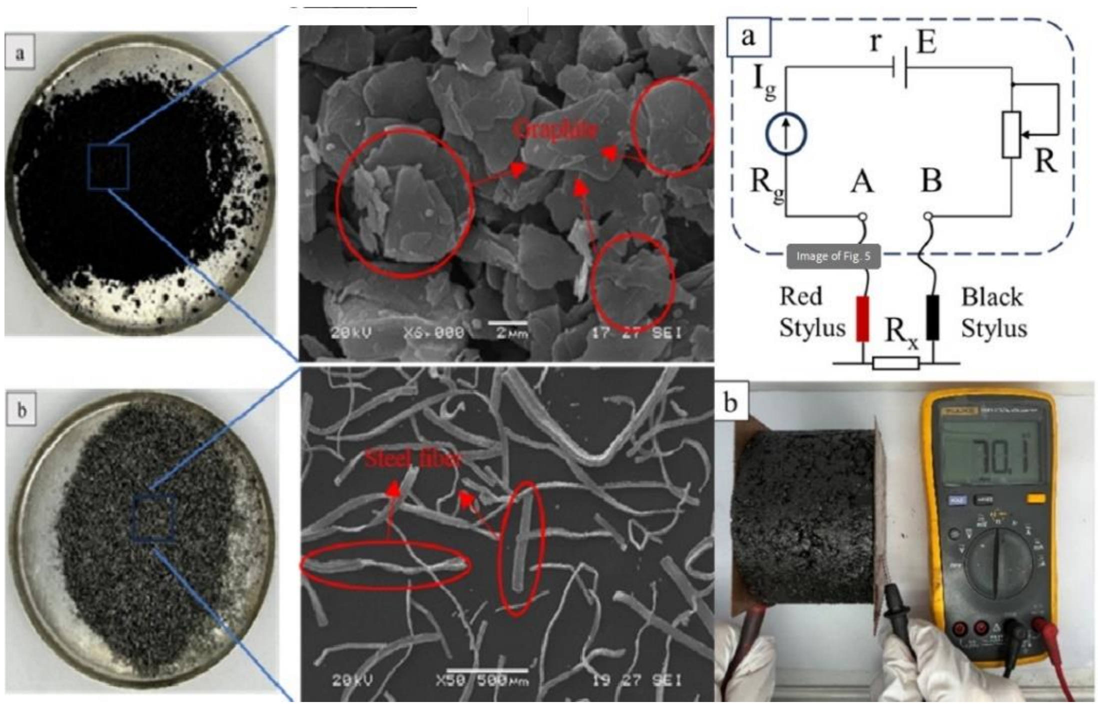

Figure 26: Conductive additives (a. graphite; b. steel fiber). Resistance meter model and test procedure (a: resistance meter model; b: test procedure) (Li, Hu et al. 2024)

The primary role of this self-sensing asphalt concrete is to detect stress, strain, and damage, including the propagation of cracks within the pavement structure. Electrical resistivity variations provide real-time insights into structural health, enabling the early identification of issues such as voids and micro-damage. Additionally, the correlation between volumetric parameters, such as void volume, and electrical properties facilitates accurate assessment of the material's internal condition (Li, Hu et al. 2024).

This technology offers significant advantages for structural health monitoring (SHM). Intrinsic sensing capability reduces installation complexity and improves durability as it eliminates the use of external sensors. Structural health monitoring is provided by continuous monitoring of electrical properties, while the combined use of graphite and steel fibers offers a new conductivity mechanism. Sensitivity and efficiency of the sensing are further improved in the dual phase sensing system which benefits from the tunneling effect of graphite and the bridging capacities of steel fibers (Li, Hu et al. 2024).

However, several limitations and challenges have been identified. Careful balancing of sensing performance with mechanical properties requires careful optimization of the dispersion and content of conductive additives. If void volumes are greater than 6%, then resistivity shows high variability, and the measurement reliability may be affected. Field-scale validation under real-world traffic and environmental conditions remains limited, and the complex interactions between conductive additives require further investigation. Additionally, long-term performance and environmental influences on the material’s electrical properties are not fully understood (Li, Hu et al. 2024).

The performance of self-sensing asphalt concrete addresses several key criteria. High sensitivity and accuracy are demonstrated through strong correlations between resistivity and structural parameters. Minimal maintenance is required due to the intrinsic sensing functionality, and durability is supported by the robustness of the conductive additives. Although the cost of materials may increase with additive content, the long-term benefits of extended pavement lifespan and predictive maintenance justify the investment. Data analysis is enhanced by advanced correlation models linking electrical properties to structural health, and the environmental impact is mitigated by the potential for reduced material wastage and optimized maintenance schedules (Li, Hu et al. 2024).

Despite its promise, further research is needed to address existing gaps. For broader adoption, standardized methods for manufacture and evaluation of self-sensing asphalt mixtures are required. However, these systems need further exploration of long-term durability under real world conditions and the impact of environmental factors, especially temperature and humidity. Integration with digital infrastructure monitoring systems can expand the applicability of this technology and provide comprehensive solutions for modern pavement management. These efforts will ensure that self-sensing asphalt concrete becomes a practical and effective tool for improving the safety and longevity of road infrastructure (Li, Hu et al. 2024).

10.1.7 Fiber optic sensors enabled monitoring of thermal curling of concrete pavement

Fiber optic sensors offer a state-of-the-art solution for monitoring thermal curling[7] in concrete pavement slabs, addressing critical challenges in structural health assessment. This study evaluates the use of distributed fiber-optic sensors and Fabry-Perot interferometer-based inclinometers for measuring temperature, strain, and tilt angles. Distributed fiber-optic sensors employ Rayleigh scattering-based optical frequency domain reflectometry (OFDR) for high-resolution temperature and strain monitoring, achieving temperature accuracy of 0.15°C and strain resolution of 2 με. These sensors are embedded at multiple slab levels, including 5 mm from the top, middle, and 5 mm from the bottom, to capture detailed thermal and strain distributions. The Fabry-Perot inclinometer, attached to the slab's surface, measures tilt angles with ultra-high sensitivity, achieving a resolution of 20 nanoradians and tracking maximum tilt angles of 0.028° during heating (Liao, Zhuang et al. 2020).

The primary role of these sensors is to monitor thermal curling caused by temperature gradients in pavement slabs. Real-time, high-resolution data of temperature differences and strain variations is collected using distributed fiber optic sensors and peak top-to-bottom temperature difference of 10°C is detected at 32 minutes from the heating cycles. The Fabry-Perot inclinometer complements this by capturing curvature changes due to tilt, offering insights into slab deformation and structural response under thermal effects. Combining these sensors creates a complete picture of thermal curling and its associated consequences to pavement health (Liao, Zhuang et al. 2020).

The integration of these technologies introduces several advantages. Distributed fiber-optic sensors provide continuous measurements over long distances (up to 1 km) and high spatial resolution (1 cm). These systems are robust and have a high level of immunity to electromagnetic interference, and even against environmental degradation. The home-built OFDR system also cost significantly less, around €10,000, compared to commercial

[7] Thermal curling is the deformation of pavement slabs caused by temperature differences between the top and bottom surfaces, leading to upward or downward curling. Curling and warping are damage mechanisms that are only related to unreinforced concrete pavements

system of €150,000. The Fabry-Perot inclinometer, with its ultra-high tilt angle sensitivity, enhances the precision of deformation monitoring. The combination of experimental measurements and finite element modeling further validates the sensor data and reveals nonlinear thermal effects that are otherwise difficult to detect (Liao, Zhuang et al. 2020).

Despite these advancements, some limitations and challenges remain. The fragility of fiber optic sensors necessitates careful installation and protective measures. Tilt angle measurements are influenced by the inclinometer's mass in small-scale laboratory setups, though this is less impactful in field applications. The current study is limited to monitoring thermal curling without accounting for additional stressors such as traffic loads and base layer conditions. Furthermore, the sensor layout used does not fully capture nonlinearities in temperature and strain across the slab's width and depth, highlighting the need for more comprehensive sensor networks (Liao, Zhuang et al. 2020).

The study addresses several key performance criteria. High sensitivity and accuracy were demonstrated, with strain and tilt angle measurements deviating by less than 3.9% between experimental and simulated results. Maintenance requirements are minimal due to the robust design of optical fibers, which maintain stable performance over extended monitoring periods. Data analysis is enhanced by advanced numerical models that complement the experimental data, providing actionable insights for structural health management. Environmental impact is indirectly addressed by enabling predictive maintenance, which reduces material wastage and prolongs pavement life (Liao, Zhuang et al. 2020).

Several research gaps remain. Field-scale validation under real-world traffic and environmental conditions is necessary to confirm the performance of these systems in practical applications. To make the technology robust, it is necessary to understand further the interactions between thermal curling, traffic loads, and base layer conditions. In order to achieve consistent performance in across diverse applications it is essential to use standardized installation and calibration methods. Further improvements of the system could be realized by adding additional sensors to capture nonlinearity in both temperature and strain across all slab dimensions. This will allow fiber optic sensors to be used for wide scale pavement monitoring and maintenance, enabling the sustainability and safety of transportation infrastructure (Liao, Zhuang et al. 2020).

10.1.8 Fiber Optics Sensors in Asphalt Pavement State-of-the-Art Review

Fiber optic sensors represent a cutting-edge technology for monitoring the structural health and performance of asphalt pavements. This study reviews the application of Fiber Bragg Grating (FBG) sensors and Fabry-Perot (FP) interferometry sensors, which offer exceptional sensitivity and precision for measuring strain, temperature, and stress. FBG sensors operate by utilizing diffraction gratings in optical fibers. Thus, strain or temperature are detected with 1.2 pm/με or 10 pm/°C sensitivity respectively. They are also capable of measuring strain over 0 to 10,000 με as well as temperature fluctuations from −40°C to 80°C for a multitude of environmental applications. Optical cavities are used in FP sensors to measure strain and stress by means of interference patterns that give ultra precise readings. The sensor types are both embedded in asphalt layers as point sensors inserted into small cavities or glued to protective polymeric proof bodies designed to assist in stress transfer compatibility and FP sensors typically into small core hole cavities to minimize disturbance (Kara De Maeijer, Luyckx et al. 2019).

The primary role of these sensors is to enable non-destructive, real-time monitoring of pavement health. The strain and temperature variations within the pavement layers are detected using FBG sensors, while FP sensors provide very accurate strain and stress measurements and support a better understanding of the pavement deformation and load response. Fiber optic sensors are an essential tool for long term monitoring of pavement deformation, rutting performance, and general structural stability under traffic and environmental loads owing to their capabilities. This also includes the integration of distributed sensing using FBG arrays for monitoring strain and temperature over lengths of 10 to 100 meters, supporting traffic classification and weigh-in motion (WIM) systems (Kara De Maeijer, Luyckx et al. 2019).

Several advantages of fiber optic sensors have been identified. These sensors are highly sensitive, with FBG sensors capable of detecting strain changes as small as 0.01 με and temperature variations as minimal as 0.1°C. They are durable, with a lifespan more than 10 years under standard conditions, resistant to environmental degradation, to electromagnetic interference and to cyclic loading of about 10 million cycles. They offer the desirable characteristics which make them reliable tools in pavement health monitoring in diverse and challenging environments. Additionally, such algorithms of advanced data analysis support real time processing of strain and temperature data for predictive maintenance and pavement management systems(Kara De Maeijer, Luyckx et al. 2019).

However, some limitations and challenges persist. FBG and FP sensors are fragile and therefore, require robust packaging and careful installation to avoid damage. Performance variability is caused by placement inconsistencies, and the sensors only sense cracks if the damage is close to them. In addition, these sensors have a higher initial cost of €1,000–€3,000 per unit than existing monitoring systems, making it difficult for their widespread adoption. However despite these costs, due to the reduced maintenance needs and also the vastly lengthened lifespan of pavements made possible through early fault detection, the money spent is justified (Kara De Maeijer, Luyckx et al. 2019).

The study addresses several important performance criteria. Reliable micro strain and temperature variations detection was demonstrated with high sensitivity and accuracy. They have low maintenance requirements because the sensors are durable and able to operate for long periods of time. Cost considerations are justified by the reduction in maintenance needs and extended pavement lifespan facilitated by early fault detection. Next, real-time monitoring and structural evaluations are furthered advanced by advanced data analysis algorithms. It is acknowledged that the environmental impact of the sensors is not fully discussed, but their utility in providing the ability for preventive maintenance indirectly minimizes material wastage and promotes sustainability (Kara De Maeijer, Luyckx et al. 2019).

Several research gaps have been identified in the field. Consistent and reliable performance of fiber optic sensors in asphalt pavements requires standardization of methods for embedding the sensors into the pavement. Validation of these sensors in field under heavy traffic and extreme environmental conditions is also limited. The sensors function within a −40 to 80°C temperature range, although durability under temperatures greater than 80°C or repeated freeze-thaw cycles is yet to be determined. Finally, fiber optic sensors integrated with digital pavement management systems for large-scale infrastructure monitoring is an area for further development. Addressing these gaps will promote use and improve the applicability of fiber optic sensors to inform pavement health monitoring (Kara De Maeijer, Luyckx et al. 2019).

10.1.9 Monitoring Structural health status of asphalt pavement using intelligent sensing technology

SmartRock sensors represent an advanced technology for monitoring the structural health of asphalt pavements, offering significant improvements in detecting stress, temperature variations, and crack propagation. These wireless sensors are multifunctional, integrating tri-axial stress gauges, accelerometers, gyroscopes, magnetometers, and temperature sensors into a compact, durable package made from acrylonitrile butadiene styrene (ABS) and nylon. SmartRock sensors are embedded at specified depths within asphalt layers, such as 0.06 m above the subbase, and spaced at intervals of 0.3 m to monitor localized stress and damage. The sensors operate with an acquisition frequency of 300 Hz, enabling real-time data collection and transmission via Bluetooth (Wang, Han et al. 2022).

The primary function of the SmartRock sensors is to monitor stress, temperature and fracture propagation in asphalt pavement. Temperature measurements are key to calibrating the stress data, the accuracy of which changes depending on the environmental conditions. The sensors were able to detect initiation of crack propagation at a load of 1.96 kN and capture peak unstable fracture load at 2.97 kN under three-point bending (TPB) tests. Early identification of micro cracks transitioning into macro cracks can be achieved with this capability of offering insights into pavement health and the possible failure points (Wang, Han et al. 2022).

The applications of this technology extend to both localized and global pavement health monitoring. Localized stress and crack data collected by SmartRock sensors are complemented by global evaluations using geostatistical models such as Kriging. This approach demonstrated high accuracy, with a correlation coefficient (R^2) exceeding 0.9 and an average relative error (ARE) below 10% when using 50% of the sensor data as training sets (Figure 28). Additionally, a Damage Index (DI) was developed to quantify the severity of damage, with values reaching 66.5% near cracks and decreasing to 5.3% in less affected zones. These advancements underscore the system's capability to assess pavement performance and guide targeted maintenance strategies (Wang, Han et al. 2022).

Several advantages of SmartRock technology are evident. It enables real time stress monitoring with high sensitivity and accuracy, greatly reducing reliance on large sensor networks. The ABS packaging is durable enough to require minimal maintenance as it consistently performs in controlled laboratory conditions. In addition, the integration of sensor data with finite element (FE) models increases the reliability of stress distribution predictions, and Kriging based statistical models are capable of accurate interpolation in areas not monitored. This innovations contributes to the cost effective pavement management by optimizing sensor placement and decreasing number of sensors. (Wang, Han et al. 2022).

However, limitations remain. Under extreme temperatures and high loads such as those encountered in field conditions, the robustness of SmartRock sensors has not been fully validated. The sensors have inherent wireless nature which can lead to susceptibility issues, such as data transmission noise, or delays. Furthermore, a reduction in crack detection sensitivity with distance from the sensors is also evident, stressing the necessity of optimal placement of the sensors to collect key information (Wang, Han et al. 2022).

Figure 27: Three different types of smart rock sensors

This study addresses several important performance criteria. The SmartRock sensors demonstrated high sensitivity to stress variations and achieved an accuracy with an R^2 value exceeding 0.9 in stress prediction models (Figure 28). Durability was confirmed through repeatable laboratory tests, and minimal maintenance was required due to the robust sensor design. Cost-specific data were not provided in the study, however, market information indicates that SmartRock sensors are available at approximately €125 to €155 per unit (GIATEC 2024), depending on the model and cable length. The use of advanced geostatistical models to minimize the number of sensors suggests a cost-effective implementation strategy. Environmental impact is mitigated through predictive maintenance, which reduces material waste and extends pavement lifespan. Regarding the Technology Readiness Level (TRL), SmartRock sensors are commercially available and have been implemented in various projects, indicating a TRL of 9, which corresponds to actual system proven in operational environment (Wang, Han et al. 2022).

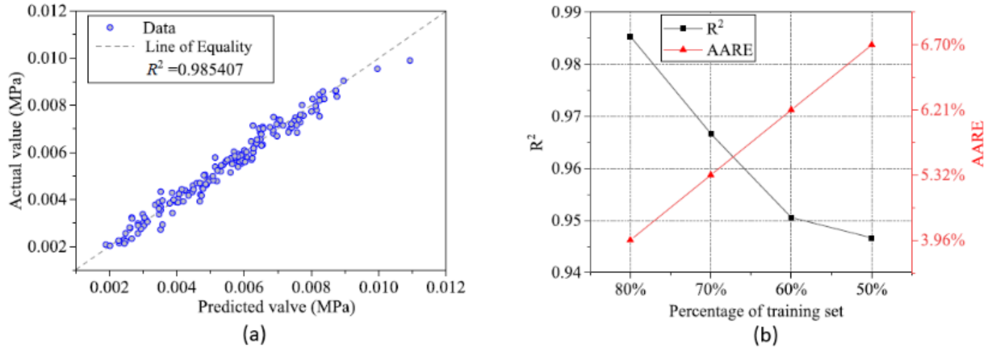

Figure 28: Correlation between actual ABAQUS FE values and Kriging predictions (a), Variation in prediction accuracy of spherical models with the proportion of the training set (b) (Wang, Han et al. 2022).

The study identified research gaps in terms of sensor performance to be further assessed under real world condition. Additional exploration of the robustness of the Kriging model under noisy data and varying stressors is also needed. Expanding sensor networks and refining placement strategies are recommended to improve sensitivity to cracks and assess the combined effects of multiple stressors. Eliminating these data gaps will help fill a critical gap for SmartRock sensors and promote the use of smart rock sensors in further pavement monitoring and maintenance practice improvement leading to more sustainable and resilient infrastructure systems (Wang, Han et al. 2022).

10.1.10 Piezoresistive response of MWCNTs-Epoxy with load-sensing capability

The use of MWCNTs-Epoxy composites as self-sensing materials presents a promising solution for structural health monitoring (SHM) in pavements. This study focuses on the development of a piezoresistive composite material, incorporating Multi-Walled Carbon Nanotubes (MWCNTs) as conductive fillers embedded in an epoxy resin matrix. The composite leverages the piezoresistive effect, wherein changes in resistance correspond to applied stress or strain. Prepared as cylindrical specimens with a diameter of 150 mm and a height of 170 mm, the material undergoes gyratory compaction and subsequent processing for resistance measurement (Figure 29). The hybrid resistance measuring method employs copper foil electrodes, ensuring smooth electrical signal acquisition and reduced noise-to-signal ratios (Huang, Wang et al. 2024).

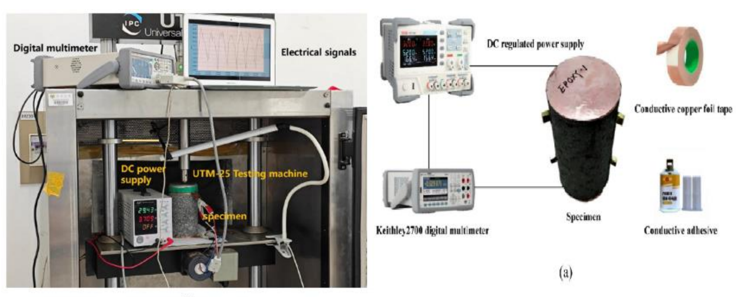

Figure 29: Resistance measurement of MWCNTs/Epoxy mixtures (Huang, Wang et al. 2024).

The primary role of this composite is to monitor stress and strain by detecting resistance changes under applied loads. The material achieves a gauge factor (GF) of up to 150, significantly higher than that of conventional materials, demonstrating exceptional sensitivity. It operates effectively within a temperature range of 0°C to 60°C and under loading frequencies of 1 Hz to 10 Hz, maintaining reliable performance across various conditions. These properties highlight the material's potential for real-time monitoring of pavement structural integrity (Huang, Wang et al. 2024).

The application of MWCNTs-Epoxy composites extends to autonomous stress and strain detection in pavement layers, contributing to enhanced structural health monitoring. Notable advantages of the material include high sensitivity to small stress variations and consistent performance for a range of loading conditions. Innovations in the preparation process, such as high-speed shear dispersion at 3000 rpm for 30 minutes, ensure uniform MWCNT distribution, enhancing the conductive network within the composite. Dense copper foil electrodes are used which minimize contact resistance and further improve signal clarity(Figure 30) (Huang, Wang et al. 2024).

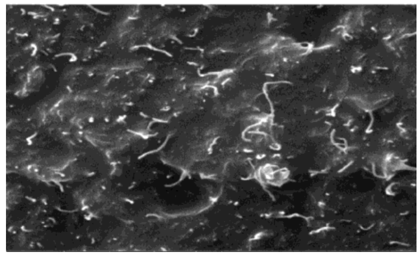

Figure 30: : Scanning Electron Microscopy of carbon nanotube-modified epoxy resin

Despite these advancements, there are some limitations that still remain. The high viscosity of asphalt complicates the dispersion of MWCNTs, leading to agglomeration at MWCNT filler contents exceeding 3.5% by weight of the epoxy resin. Optimal piezoresistive performance is observed at a filler content of 2.5%, beyond which the piezoresistive effect diminishes due to saturation of the conductive network and reduced interaction between MWCNTs and the matrix. Additionally, the material's field performance under traffic loads and varying environmental conditions has yet to be fully validated, underscoring the need for further research in real-world applications (Huang, Wang et al. 2024).

The performance of the MWCNTs-Epoxy composite meets several key criteria. The material demonstrates high sensitivity, with fractional resistance changes accurately reflecting strain variations. Laboratory tests confirm consistent and repeatable readings with low noise-to-signal ratios, ensuring accuracy. The cost of the composite is relatively low due to the use of commercially available materials such as epoxy resin and MWCNTs. Maintenance requirements are minimal, owing to the material's robustness and durability under cyclic loading and temperatures ranging from -15°C to 60°C. Advanced data analysis methods, including the calculation of fractional resistance change (FCR) and Temperature Resistance Coefficient (TRC), enhance the interpretation of sensing data. Environmentally, the material facilitates early damage detection, reducing material waste and extending the lifespan of pavements (Huang, Wang et al. 2024).

Several research gaps have been identified in this study. To confirm its practical applicability, the material should be real world validated under traffic loads and extreme weather conditions. Consistent performance requires standardized preparation and embedding techniques to be defined. In addition, the effects of environmental factors, such as humidity, on the capability of composite to sense need further investigation. Addressing these gaps will facilitate the execution of the broader usage of MWCNTs-Epoxy composites in the advanced pavement monitoring system in order to better ensure infrastructure sustainability and safety (Huang, Wang et al. 2024).

10.1.11 Piezoresistive response of self-sensing asphalt containing carbon fiber

The development of self-sensing asphalt concrete (SSAC) incorporating carbon fiber offers a promising solution for traffic monitoring and pavement health evaluation. This study focuses on the integration of carbon fibers into asphalt concrete to create a conductive network capable of monitoring stress and strain through piezoresistive responses. The SSAC utilizes a sandwich structure, embedding galvanized iron electrode mesh within the asphalt layers at intervals of 31.75 mm, with the final specimen height measuring 63.5 mm (Figure 31). Carbon fibers, measuring 6 mm in length, enable conductivity via tunneling and contact transfer mechanisms, forming a stable sensing network within the composite (Cui, Feng et al. 2024).

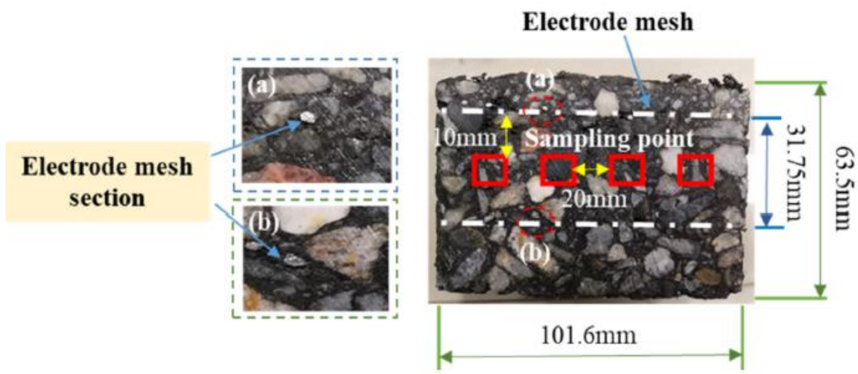

Figure 31: The location of the sampling point (Cui, Feng et al. 2024).

The primary role of SSAC is to monitor stress and strain through changes in electrical resistance under applied loads. The material demonstrates effective performance under stress amplitudes ranging from 0.18 MPa to 0.9 MPa, with fractional changes in resistance (FCR) varying from 50% for SSAC-2% to 4.5% for SSAC-10%. Sensitivity is optimized at 6% carbon fiber content, where the material achieves a peak Gauge Factor (GF) of approximately 8. This configuration allows the SSAC to reliably detect stress and strain variations, making it suitable for traffic volume monitoring, vehicle weight estimation, and the detection of vehicle speed and distance (Cui, Feng et al. 2024).

The SSAC offers several key advantages, including high sensitivity, stable performance under cyclic loads, and a strong correlation between electrical resistance and various loading characteristics. Optimal performance is achieved at 6–8% carbon fiber content, balancing sensitivity and durability. Innovations in this study include the introduction of a sandwich structure to enhance the integration of electrode mesh, enabling effective signal acquisition and reduced noise. The material's ability to establish consistent correlations between electrical resistance and external loading conditions further highlights its potential for advanced pavement monitoring systems (Cui, Feng et al. 2024).

Despite its advantages, certain limitations and challenges remain. Excessive noise in resistance readings is observed at low carbon fiber contents (<4%), while sensitivity declines at higher concentrations (>8%). These findings necessitate careful optimization of carbon fiber concentration to maintain peak performance. In addition, testing under real world traffic and environmental conditions has been confined, and questions remain on the material's long term durability and performance (Cui, Feng et al. 2024).

The study addresses several key performance criteria. At 6% carbon fiber content, 98.39% accuracy can be achieved by the SSAC with good sensitivity to stress and strain variations. The material is durable and has minimal maintenance requirements due to the stable nature of the conductive pathways. Under stresses as high as 0.9 MPa and cyclic loading conditions, the SSAC shows evidence of durability. FCR calculations and other advanced data analysis techniques are used to increase interpretation of resistance changes, and predictive maintenance. Early damage detection, reduction of material waste and increased longevity of pavements are mechanisms to indirectly address environmental impact (Cui, Feng et al. 2024).

Validation of the SSAC in the field under real traffic loads and weather is necessary to confirm the applicability of the SSAC to practice. Long term durability under extreme conditions is still to be further explored where the conductive network is concerned. Fabrication and embedding must also be standardized in order to offer consistent performance from installation to installation. Addressing these gaps will enable SSAC to be a viable Surveillance and Advanced Control tool for advanced pavement monitoring and traffic management systems (Cui, Feng et al. 2024).

10.1.12 Self-sensing behavior and mechanical properties of carbon nanotubes-epoxy resin composite for asphalt pavement strain monitoring

The development of carbon nanotubes-epoxy resin composites introduces a highly sensitive and durable solution for strain monitoring in asphalt pavements. This study focuses on the use of aligned Multi-Walled Carbon Nanotubes (MWCNTs) as conductive fillers within an epoxy resin matrix to form a self-sensing material. The MWCNTs, with a purity of 95 wt%, a diameter of 10–20 nm, and a length of 30–100 µm, create a 3D conductive network that responds to strain-induced deformations. The electrical conductivity of the aligned MWCNTs exceeds 1250 S/cm, while the elasticity modulus of the composite reaches 1250 MPa at a CNT content of 0.8 wt%. Although this value is lower than the typical stiffness of asphalt surface layers, which can range from 2500 MPa to 5000 MPa depending on temperature, loading rate, and bitumen type, the composite shows promise for monitoring applications where stiffness compatibility with specific pavement conditions is not critical. The material is cured and processed into cylindrical specimens for embedding within pavement layers, enabling direct integration into asphalt structures (Figure 32) (Xin, Liang et al. 2020).

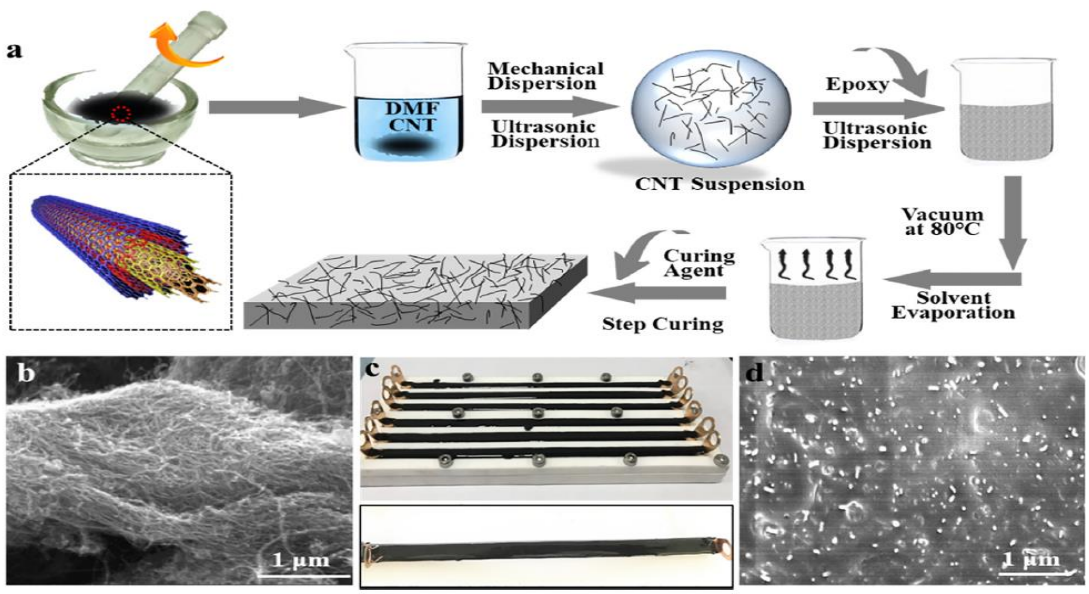

Figure 32: Preparation and morphology of nanocomposites. a. Schematic diagram of the key steps in fabricating the composites strain sensor b. SEM image of aligned MWCNTs (Xin, Liang et al. 2020).

The primary role of the composite sensor is to monitor strain by detecting changes in electrical resistance caused by deformation of the conductive network. The sensor demonstrates exceptional performance within a strain range of 0–1000 µε, achieving a gauge factor (GF) of 26.04 at an optimal CNT content of 0.8 wt%. This sensitivity significantly surpasses that of traditional metal strain sensors, which typically exhibit a GF of approximately 2. Durability tests confirm stable performance over 100,000 cycles under cyclic loading within a strain range of 0–100 µε, highlighting the material's suitability for long-term monitoring. The sensor also exhibits a prompt response time, ensuring real-time detection of strain-induced changes (Xin, Liang et al. 2020).

The application of this technology is geared toward monitoring micro-strain in asphalt pavements, enabling the real-time detection of deformation for early damage assessment. Notable advantages include its high sensitivity, superior mechanical properties, and the ability to tune the composite's tensile strength and stiffness by adjusting CNT content to match different pavement layers. The study introduces an innovative dispersion method combining grinding, ultrasonic dispersion, and vacuum curing, which effectively minimizes CNT agglomeration, ensuring uniform conductivity throughout the composite. This advancement addresses a common challenge in CNT-based materials, enhancing both mechanical and sensing performance (Xin, Liang et al. 2020).

Despite its advantages, the material faces several limitations. CNT agglomeration at higher contents (>1.2 wt%) reduces both mechanical and sensing efficiency, indicating an optimal concentration range for performance. Hysteresis in resistance response is observed during cyclic loading, with a hysteresis value of 8.3%, attributed to strain transfer delays between the epoxy matrix and the CNT network. Additionally, the material's validation under field conditions – extreme temperatures and environmental stressors – remains to be done (Xin, Liang et al. 2020).

The composite addresses several critical performance criteria. It achieves high sensitivity with a gauge factor of 26.04 and maintains accuracy within the strain range of 0–1000 με, as validated over 100,000 loading cycles. The cost of the material is expected to be moderate due to the use of commercially available components, including epoxy resin and CNTs. Maintenance requirements are minimal, thanks to the composite's durability and stable resistance response under repetitive loading. Advanced data analysis models facilitate real-time monitoring with minimal computational demands, while early detection of micro-cracks and deformation reduces material waste and extends pavement service life, thereby mitigating environmental impact (Xin, Liang et al. 2020).

Several research gaps are identified. To verify the performance of the composite in real world traffic and environmental conditions, field scale validation is needed. Further work is needed on the effect of extreme temperatures and humidity on sensing behavior and durability. Furthermore, the preparation methods and techniques for embedding need to be standardized to ensure a consistent performance regardless of application. Addressing these gaps will enable the widespread adoption of MWCNTs-epoxy resin composites in strain monitoring, contributing to the sustainability and reliability of modern pavement infrastructure (Xin, Liang et al. 2020).

10.1.13 Ultra-low detection limit self-sensing nanocomposites with self-assembled conductive microsphere arrays for asphalt pavement health monitoring

The use of self-sensing nanocomposites with self-assembled conductive microsphere arrays represents a significant advancement in asphalt pavement health monitoring. This study highlights the development of these nanocomposites, which integrate conductive microspheres with Multi-Walled Carbon Nanotubes (MWCNTs) to form a 3D conductive network. Chemical modifications, such as amino functionalization, enhance the dispersion and stability of CNTs, optimizing the conductive pathways for strain sensing. The sensors are encapsulated into H-shaped rod structures, measuring 14 cm in length and 1 cm in diameter, for direct embedding within pavement layers (Figure 33, 34) (Su, Jiao et al. 2024).

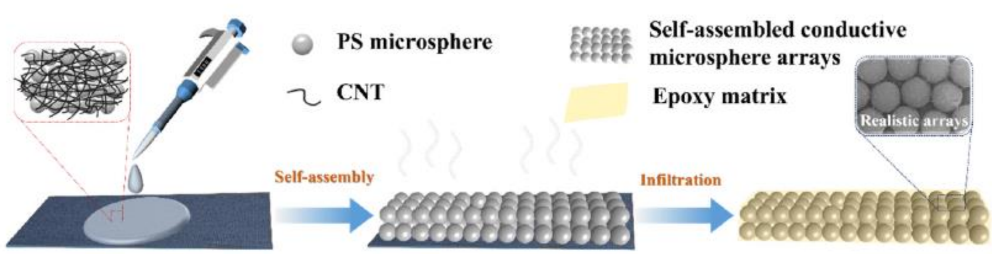

Figure 33: Schematic of the preparation process of sensing nanocomposites (Su, Jiao et al. 2024).

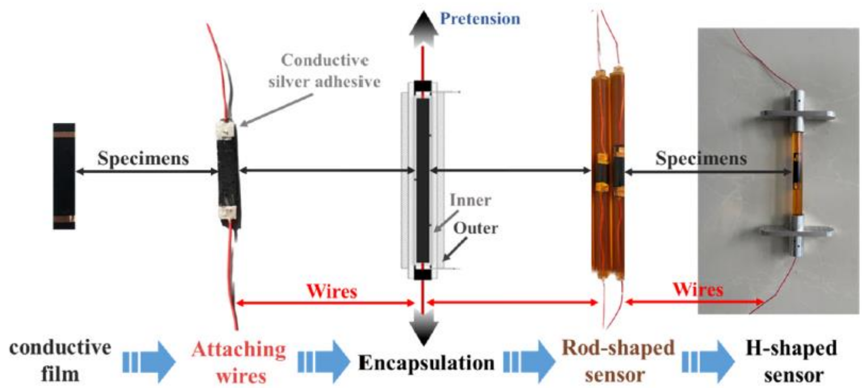

Figure 34: Encapsulation process of self-sensing nanocomposites with enhanced durability and compatibility for engineering applications (Su, Jiao et al. 2024).

The primary role of these sensors is to monitor micro-strain in asphalt pavements by detecting changes in electrical resistance. The system demonstrates an ultra-low detection limit of 0.0005% strain (5 με), with a gauge factor (GF) of 13.2. The sensor exhibits a rapid response time of 19 ms for stretching and 26 ms for returning and maintains durability over 100,000 load-unload cycles, highlighting its capability for long-term, high-frequency strain monitoring. The strain sensing range extends to 0–1700 με, further emphasizing the material's suitability for real-time pavement health assessment (Su, Jiao et al. 2024).

The application of these nanocomposites is geared toward proactive health monitoring of asphalt pavements, enabling the real-time detection of micro-strains to guide maintenance and prevent crack propagation. The material offers several advantages, including exceptional sensitivity, robustness under high-frequency loading scenarios, and a well-ordered 3D conductive network that minimizes CNT agglomeration. Innovations introduced in this study include the use of self-assembled conductive microspheres, which reduce aggregation and ensure uniform conductivity, thereby enhancing strain-sensing performance (Su, Jiao et al. 2024).

Despite these advancements, certain challenges remain. The fabrication is a multi-step self-assembly and encapsulation process that increases complexity, also may limit scalability. However, the limitation to CNT agglomeration at higher concentrations remains a barrier to providing high conductivity and sensing accuracy. Also, while laboratory and controlled field tests confirm the sensor's performance, there is little data available relating their performance under extreme environmental conditions, namely temperature fluctuations, moisture (Su, Jiao et al. 2024).

The sensors address several critical performance criteria. Their high sensitivity is demonstrated by a detection limit of 5 με, with a GF of 13.2, making them suitable for detecting micro-strain in pavements. High accuracy is validated through field tests under varying vehicular loads and speeds. The sensors exhibit excellent durability, maintaining consistent performance over 100,000 cycles, and require minimal maintenance due to their robust design. Advanced data analysis capabilities, supported by a high-frequency data acquisition system operating at 1000 Hz, enable dynamic response tracking. While specific cost details are not provided, the use of readily available materials such as CNTs and epoxy resins suggests moderate production costs. Environmental impact is mitigated through early damage detection, reducing road deterioration and conserving resources (Su, Jiao et al. 2024).

Several research gaps have been identified. To confirm their practical applicability, the sensors need to be long-term validated under real world traffic loads and harsh environmental conditions such as extreme temperatures and moisture. There remain several issues to consider in the integration of these sensors into large scale intelligent transportation systems and compatibility with existing monitoring infrastructure. The second requirement is in addition to reproducibility and scalability: standardized fabrication and installation methods must be developed to ensure reproducibility and scalability. Eliminating these gaps will enable the effective utilization of self-sensing nanocomposites and help pioneer the sustainability and safety of modern pavement infrastructure (Su, Jiao et al. 2024).

10.2 Appendix B: Results Summary and Connection to Research Questions

What are the current sensor technologies available for pavement engineering, and which of these are most suitable for use, considering their cost-effectiveness, reliability, and ability to withstand environmental conditions and operational demands?

- The study identifies Fiber Optic Sensors (FBG and DOFS), Self-Sensing Asphalt, and Smart Aggregates/SmartRock Sensors as the leading technologies for pavement monitoring.

What are the predominant types of damage in Dutch roads, and how can sensor technologies be used to monitor and predict these damages?

- The major damage types observed in Dutch roads include rutting, cracking, raveling, unevenness, and potholes. Fiber Optic Sensors are best suited for monitoring strain and stress, ideal for motorways where deformation tracking is critical. Piezoelectric Sensors are effective in detecting crack initiation, making them a good choice for provincial roads. Smart Aggregates and Wireless Sensors are recommended for municipal roads, where cost-effective solutions are required.

What is the optimal placement of sensors and the key operational parameters for effective sensor-based road monitoring systems?

- It is suggested that Sensors be installed under wheel paths to monitor stress and strain.

What are the current advancements in sensor technologies for pavement engineering, including emerging options such as self-sensing nanocomposites, carbon nanotube-embedded materials, and smartphone-based monitoring applications?

- Advancements include self-sensing composites that integrate carbon nanotubes and other conductive materials into asphalt, allowing stress and strain monitoring without external sensors. These technologies show promise but require further research and validation.

What challenges and limitations do these sensor technologies face in terms of integration with asphalt and data accuracy?

- High cost and installation complexity in Fiber Optic Sensors. It requires material optimization to ensure uniform dispersion of sensing materials and self-sensing asphalt. Need real-world durability and data accuracy validation in Smart Aggregates & Wireless Sensors.

How do the costs and benefits of current sensor technologies compare, and what criteria can be used to assess their suitability for use in pavement engineering?

- The Multi-Criteria Analysis (MCA) evaluates sensors based on sensitivity, accuracy, durability, cost, maintenance, and environmental impact. Fiber Optic Sensors rank highest but have a high upfront cost. Wireless and Smart Aggregates provide a balance between cost and functionality.

What are the main types of damage observed in Dutch roads (e.g., rutting, cracking, raveling, unevenness)?

- The study confirms that the most common damages are rutting, cracking, raveling, unevenness, and potholes.

How do damage types vary across the three categories of Dutch roads (motorways, provincial roads, and municipal roads)?

- Motorways: High rutting and raveling due to heavy truck loads.
- Provincial Roads: More fatigue cracking and unevenness due to environmental factors.
- Municipal Roads: Higher risk of potholes and surface wear due to lower maintenance.

What specific parameters need to be measured to predict different types of road damage effectively (e.g., stress, strain, temperature, moisture)?

- Key parameters: Stress, strain, temperature, and moisture. Stress and strain sensors are crucial for detecting deformation, while moisture and temperature sensors help predict environmental damage.

Where should sensors be placed on the road surface (e.g., side, middle, under the wheel path)?

- Under wheel paths for stress measurement. At the edges of municipal roads to monitor crack formation.

How frequently should measurements be taken to capture meaningful trends in road performance, and how does the age of the road after construction influence the initiation of these measurements?

- Real-time monitoring is recommended for fiber optic sensors. Measurement frequency should be adjusted based on road type and expected wear rates.

Should monitoring focus on heavy vehicles (e.g., trucks) rather than light vehicles, given their disproportionate impact on road wear and tear?

- The study supports prioritizing heavy vehicle monitoring, as they contribute significantly to rutting and fatigue cracking.