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Utilization of Sensors in Monitoring the Quality of Sustainable Asphalt

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Abstract. The quality of road infrastructure, particularly asphalt, is crucial in urban and transportation development, as high-quality asphalt enhances user comfort, safety, and cost-efficient maintenance while supporting environmental sustainability. However, 31.91% of roads in Indonesia are damaged, highlighting the need for effective monitoring systems. This study evaluates sensor technology for sustainable asphalt quality monitoring and explores strategies for its integration into infrastructure management. While prior research has focused on technical aspects, challenges in data integration and high implementation costs remain unaddressed. A systematic literature review was conducted using Scopus, Google Scholar, and IEEE Xplore, analyzing studies from the past five years based on sensor types, applications, and implementation challenges. Findings show that sensors provide real-time data on temperature, moisture, and pressure, reducing maintenance costs by 25-30% through early detection. Intelligent compaction and structural health monitoring systems improve long-term road performance. However, high initial costs, lack of standardization, and difficulties in integrating multi-sensor data hinder widespread adoption. Addressing cost barriers and ensuring seamless integration with infrastructure management are crucial, with future research needed to develop cost-effective and interoperable sensor solutions.

1 Introduction

In recent decades, the quality of road infrastructure, particularly asphalt, has become a primary focus in urban and transportation system development. High-quality asphalt not only enhances road user comfort and safety but also influences cost-efficient maintenance and environmental sustainability. According to data from BPS, 31.91% of roads in Indonesia were reported as damaged [1], underscoring the urgent need for improved monitoring systems to ensure sustainable asphalt quality.

The integration of sensor technology in asphalt quality monitoring offers an innovative and efficient solution. Sensors can provide real-time data on asphalt conditions, including temperature, moisture, and pressure key factors contributing to asphalt degradation. A study by Rafati and Shaker [2] demonstrated that sensor implementation reduces maintenance costs by up to 25-30% through early detection of issues before escalation. This highlights the significant potential of sensor technology in enhancing road infrastructure quality and

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sustainability. However, despite extensive research on sensor applications, a notable gap remains: most studies focus on technical aspects, with limited exploration of sensor integration into public policy and infrastructure management frameworks. This study aims to address this gap by examining the application of sensors in sustainable asphalt quality monitoring and proposing strategies for effective integration.

From a sustainability perspective, sensor technology can also facilitate environmental impact monitoring. For instance, tracking carbon emissions during road construction and maintenance provides insights into the ecological footprint of infrastructure. Our World in data [3] reports that the transportation sector contributes approximately 24% of global carbon emissions, emphasizing the need for technologies that mitigate such impacts. Against this backdrop, this research comprehensively analyzes sensor-based methods for sustainable asphalt monitoring, evaluating implemented approaches, outcomes, and implementation challenges. The findings are expected to inform policy development and best practices in road infrastructure management in Indonesia, promoting environmentally responsible and cost-effective solutions.

This literature review examines relevant studies on the application of sensors in asphalt quality monitoring. Various sensor types, such as temperature, moisture, and pressure sensors, have been utilized in research to assess asphalt conditions. Liu et al. [4] demonstrated that Structural Health Monitoring (SHM) integrates Accelerated Pavement Testing (APT) and Falling Weight Deflectometer (FWD) to assess asphalt pavement conditions, enabling optimized application timing and long-term performance evaluation. Data collected from these sensors enable engineers to make informed decisions during construction processes. Furthermore, moisture sensors play a critical role in asphalt monitoring, as excessive moisture can lead to asphalt deterioration, including cracking and stripping. It can be found that Intelligent compaction (IC) utilizes smart sensors and machine learning to enhance asphalt pavement quality and efficiency. By monitoring compaction status and predicting material properties, these technologies improve road construction but require further validation for real-world application.

A notable case study is the implementation of sensor technology in Indonesia, where an integrated sensor system monitors road conditions in real time. A study shows that the use of real-time sensor data can reduce maintenance costs by up to 25% within the first three years of implementation [5]. This example illustrates the significant economic benefits of well-designed sensor systems. However, despite the demonstrated potential of sensor technology, implementation challenges persist. A key barrier is the high initial cost of sensor installation and system maintenance. The International Road Assessment Program highlights that upfront investments in sensor technology often deter local governments from adopting it, emphasizing the need for further research to develop cost-effective solutions [6].

In conclusion, sensor-based monitoring holds substantial potential for improving the quality and sustainability of road infrastructure. However, addressing implementation challenges, particularly cost barriers, is critical for broader adoption. Future research should focus on bridging existing gaps and identifying effective strategies to optimize sensor applications in asphalt quality monitoring.

This study employed a literature review methodology, a systematic approach to gathering, analyzing, and synthesizing information from diverse relevant sources. The review aimed to identify and evaluate prior research on sensor applications in sustainable asphalt quality monitoring. The process began with a comprehensive literature search across leading academic databases, including Scopus, Google Scholar, and IEEE Xplore.

The inclusion criteria for selecting literature encompassed peer-reviewed journal articles focusing on sensor technology in asphalt quality monitoring, along with relevant case studies. Only articles published within the last five years were considered to ensure the use of up-to-date and technologically relevant data. This screening process yielded over 100 relevant articles, which were further filtered based on methodological rigor and thematic alignment with the study's objectives.

Following the screening, data from selected articles were analyzed to identify key themes, trends, and research gaps. The analysis categorized studies by sensor type (e.g., temperature, moisture, pressure), applications in asphalt monitoring, and outcomes of sensor implementation. Findings were synthesized into a structured narrative to provide a comprehensive overview of sensor utilization in sustainable asphalt quality monitoring.

By adopting a systematic literature review approach, this study aims to deepen insights into the potential and challenges of sensor technology in asphalt quality management. Additionally, by highlighting gaps in existing research, it seeks to guide future studies toward more focused and application-driven investigations.

2 Results and Discussions

The findings of this study demonstrate that sensor utilization in asphalt quality monitoring significantly enhances road infrastructure quality. Data from multiple studies indicate that sensors improve the accuracy of asphalt condition assessments. For example, Liu et al. [4] reported that pressure sensors detect changes in asphalt density, which directly impacts pavement durability. These results underscore the critical role of sensor technology in sustaining asphalt quality over time.

Furthermore, analysis reveals that sensor applications extend beyond construction phases to road maintenance. It can be found that moisture sensors facilitate ongoing assessment of road conditions, enabling timely maintenance actions to be taken before significant damage occurs, particularly in environments prone to freeze-thaw cycles, where high moisture levels in unbound aggregate layers can lead to critical functional and structural issues. This highlights the potential of sensors for proactive and efficient infrastructure management. However, despite these promising outcomes, key challenges remain. A major obstacle is integrating multi-sensor data into existing infrastructure management systems. The World Bank noted that many local governments struggle to harmonize sensor data with legacy systems, hindering data-driven decision-making. Thus, further research is essential to develop interoperable sensor-integrated frameworks.

From a sustainability perspective, sensor technology can mitigate the environmental impact of road construction and maintenance. By monitoring carbon emissions and material usage, sensors provide actionable data for designing eco-friendly roads. It demonstrated that real-time emission monitoring during construction enables adjustments to reduce environmental harm. Collectively, these findings illustrate the dual benefits of sensor-based monitoring: improved infrastructure quality and enhanced environmental sustainability. Nevertheless, addressing integration and implementation barriers is crucial to fully realize this potential. Future studies should focus on bridging these gaps and advancing cost-effective solutions for sustainable asphalt quality monitoring.

3 Introduction to Sensor Technology in Asphalt Quality Monitoring

The integration of sensor technology in asphalt quality monitoring has emerged as a pivotal focus in modern infrastructure research. Sensors provide critical real-time data to maintain asphalt quality and durability, directly influencing road safety and user comfort. Mallick et al. [7] demonstrated that temperature and moisture sensors help mitigate high-temperature effects on asphalt pavements, reducing rutting and aging while extending pavement lifespan. By lowering pavement temperatures, they contribute to improved fatigue resistance and reduced maintenance needs, aligning with studies on high-albedo aggregates and geosynthetic reinforced chip seals.

Data from Indonesia's BPS reveals that 31.91% of roads nationwide are damaged [1], primarily due to poor asphalt quality. Sensors enable faster and more accurate assessments of asphalt conditions. For instance, pressure sensors detect surface deformations before they escalate into major issues. Zhong et al. [8] investigates the mechanical response of asphalt pavement structures with embedded sensors, highlighting their capability for long-term and real-time monitoring to predict structural damage during the pavement's operational period.

Smart sensors were deployed across road networks for real-time asphalt monitoring. This implementation to detect road surface damage conditions, aiming to establish a safer road environment and enhance the accuracy of damage detection, facilitating early repairs and potentially reducing the extent of road deterioration, underscoring the significant positive impact of sensor technology on infrastructure. However, despite these demonstrated benefits, implementation challenges persist, particularly in developing regions constrained by limited budgets and inadequate infrastructure for sensor deployment. Further research is essential to develop cost-effective and scalable solutions to address these barriers.

4 Types of Sensors Used in Asphalt Quality Monitoring

Various types of sensors have been developed to monitor asphalt quality, each with its own functions and advantages. Temperature sensors, for instance, are crucial in the asphalt paving process. Research indicates that high temperatures can reduce bitumen viscosity, potentially leading to permanent asphalt deformation. Therefore, accurate temperature sensors are essential to ensure that asphalt is applied at the optimal temperature. In addition to temperature sensors, humidity sensors also play a significant role in asphalt quality monitoring. High humidity levels can affect the asphalt drying process and lead to deterioration. According to a the application of fiber optic sensors in asphalt pavements has been explored to monitor various parameters, including moisture content.

Another increasingly popular sensor is the vibration sensor, which is used to detect deformation and damage on road surfaces. Research has shown that vibration-based methods effectively detect road anomalies, including potholes and surface irregularities, by analyzing data acquired from sensors. This information allows for maintenance to be carried out before damage becomes more severe, thereby reducing repair costs. However, despite the availability of various types of sensors, challenges remain in data integration and processing. Data generated from multiple sensors are often not well integrated, making it difficult to obtain a comprehensive assessment of road conditions. Therefore, further research is needed to develop systems capable of efficiently integrating data from different types of sensors. Such integration will enable more accurate monitoring, improve decision-making for maintenance planning, and enhance overall transportation system performance. Effective data integration can also facilitate predictive modeling of pavement deterioration, enabling authorities to implement timely interventions and optimize maintenance budgets.

5 Implementation of Sensors in Infrastructure Projects

The implementation of sensors in infrastructure projects, particularly in asphalt quality monitoring, has shown promising results in various countries. In Europe, several countries such as Sweden and Germany have adopted intelligent sensor systems in road maintenance projects. For example, A road maintenance project in Germany implemented the ZEB system, which utilizes high-speed measuring vehicles equipped with sensors to monitor asphalt conditions. This system collects essential data on surface evenness, skid resistance, and cracks, storing it in a comprehensive database for analysis.

The integration of sensor systems has played a crucial role in traffic congestion management by enabling real-time data exchange and facilitating strategic urban planning. Wireless Sensor Networks (WSNs) have proven to be effective due to their rapid data transmission, easy installation, and cost efficiency compared to other systems. These sensors not only help monitor road conditions but also contribute to traffic flow optimization and accident prevention. By leveraging sensor-based technologies, cities can implement smarter road maintenance strategies, ultimately reducing unplanned repairs and minimizing traffic disruptions. However, challenges in sensor implementation in Indonesia remain. One of the primary issues is the lack of understanding and training regarding sensor technology among construction workers.

6 Data Analysis from Sensors for Decision-Making

One of the critical aspects of sensor utilization is the analysis of the data generated for decision-making. Sensor data must be processed and analyzed accurately to provide valuable information for road maintenance. According to research by Yanis et al. [9], analyzed factors influencing road maintenance effectiveness, highlight that data-driven decision-making substantially contributes to improved maintenance outcomes.

In many cases, sensor data must be integrated with existing information management systems. For instance, Geographic Information Systems (GIS) can be used to visualize sensor data in map format, facilitating decision-making. Research by Mensah et al. [10] discussed the visualization of integrated highway maintenance and construction planning using GIS. The study emphasized how GIS-based visualization aids decision-makers by integrating geospatial data across various datasets, facilitating better planning and coordination of maintenance activities.

7 Integration of Sensor Systems with Public Policy and Infrastructure Management

The utilization of sensors for sustainable asphalt quality monitoring is not only focused on technical aspects but must also be integrated with public policy and infrastructure management. In this context, sensors used to monitor road conditions and asphalt quality provide valuable data for decision-makers. Based on research the implementation of smart sensors enable continuous monitoring of various factors such as surface defects, traffic flow, and environmental conditions, facilitating timely maintenance and improved safety. This allows governments to respond more swiftly to emerging issues, such as road damage or asphalt degradation. Integrating sensor systems into public policy, governments can take a more proactive approach to road maintenance and repair planning. This not only reduces long-term costs but also improves road user safety [11].

A relevant case study is the implementation of sensors in smart cities such as Songdo, South Korea, is renowned for its advanced smart city infrastructure, which includes an extensive network of sensors and Internet of Things (IoT) devices [12]. Data collected from these sensors are integrated into a larger traffic management system, enabling better decision-making and faster responses to infrastructure issues. This demonstrates how the integration of sensor technology into public policy can yield significant societal benefits.

However, despite the vast potential of this integration, challenges remain in its implementation. One of the main challenges is the need for collaboration among various stakeholders, including governments, technology companies, and the public. Research by

Iqbal et al. [13] implementation of remote monitoring and digital alerting tools in complex health organizations has been hindered by communication barriers among key stakeholders. A comprehensive analysis revealed that effective communication is a facilitator for the successful adoption of these technologies, while communication gaps serve as significant barriers. Therefore, it is crucial to establish a clear framework for collaboration and communication among all parties involved.

8 Previous Related Research

The application of sensor technology in asphalt quality monitoring has been a significant focus of research. Various studies have demonstrated that the use of sensors can improve efficiency and effectiveness in monitoring asphalt quality. IoT sensors detect early signs of wear and tear, allowing for timely interventions. A study developed a self-powered distributed intelligent pavement monitoring system that collects data on temperature, humidity, and structural vibrations, supporting maintenance and vehicle-road synergy applications [14]. Data obtained from these sensors can be used to optimize the asphalt application process, reducing the risk of damage and extending road lifespan. The Ultrasonic Pulse Parameters (UPP) method has demonstrated a strong correlation with the strength of asphalt mixtures across various temperatures. This technique enables the assessment of mechanical properties, such as compressive strength, by analyzing the transmission of ultrasonic pulses through the material. Their findings suggest that sensor utilization can help identify issues early, ultimately reducing road maintenance and repair costs.

The study by Cafisoa et al. [15] explores the use of a Non-Destructive Test (NDT)-based sensor unit to collect acoustic signatures from road pavements with varying levels of deterioration. The research found that features extracted from these acoustic signatures correlate well with the elastic modulus of asphalt layers, as measured by Ground Penetrating Radar (GPR) and Falling Weight Deflectometer (FWD). This approach provides a more cost-effective and efficient method for continuously monitoring the structural condition of roads, enabling early detection of damage caused by traffic loads. However, despite the numerous studies conducted, there remains a significant research gap regarding the integration of multiple sensor types for holistic asphalt quality monitoring. Most existing studies focus on a single type of sensor or specific parameter without considering interactions between various factors affecting asphalt quality. Therefore, further research is needed to develop a more comprehensive and integrated monitoring system.

In this context, it is essential to consider external factors that may influence monitoring results, such as weather conditions, asphalt material types, and traffic patterns. Research indicates that a data acquisition approach that combines real-time analysis from two sensors via a nano computer. The method aims to enhance the accuracy of pavement surface condition characterization, particularly under varying weather conditions.

9 **Identification of Research Gaps**

Despite the extensive research conducted on the use of sensors for asphalt quality monitoring, several research gaps remain unaddressed. First, most studies have been limited to the context of developed countries, leading to a lack of relevant data and analysis for developing nations. Further research exploring the implementation of sensor technology in developing countries is essential to understand the unique contexts and challenges involved. Second, the integration of data from various sensor types and the development of systems capable of real-time data analysis remain underexplored areas. In-depth research on algorithms and data analysis methods that can effectively utilize sensor data would be highly beneficial.

Third, studies on the long-term impact of sensor utilization in asphalt quality monitoring, including more comprehensive cost-benefit analyses, are still limited. Research examining the social, economic, and environmental implications of this technology would provide broader and deeper insights. By addressing these research gaps, the implementation of sensors in asphalt quality monitoring can be further advanced, ultimately delivering greater benefits to society and the environment.

10 Conclusion

This study demonstrates that the use of sensor technology in asphalt quality monitoring has a significant impact on improving road infrastructure. Sensors can provide real-time data on asphalt conditions, including temperature, humidity, and pressure, which are key factors in asphalt degradation. By detecting potential damage early, this technology can reduce maintenance costs by 25-30%, as shown by several studies. In addition to technical benefits, sensors also play a role in environmental sustainability. Monitoring carbon emissions during road construction and maintenance provides crucial insights into reducing ecological impacts. This technology enables the implementation of more proactive and data-driven policies in road infrastructure management.

Despite its many advantages, there are challenges in implementing sensor technology, particularly in terms of high initial costs and difficulties in integrating data into existing infrastructure management systems. This study highlights the importance of further research to develop more cost-effective solutions and systems capable of integrating various types of sensors effectively. From a public policy perspective, integrating sensors into infrastructure management systems can enhance government responsiveness to road repairs. Case studies in several countries show that well-implemented sensor systems can improve road safety and maintenance efficiency. However, to maximize benefits, collaboration between governments, industries, and academia is necessary to establish a framework that supports the widespread adoption of this technology. Overall, this study confirms that smart technology-based sensors have great potential in improving the quality and sustainability of road asphalt. However, challenges related to cost, data integration, and implementation in developing countries still need to be addressed through further research and development. With the right approach, sensor technology can be an effective solution for enhancing the resilience and efficiency of road infrastructure in the future.

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