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Renewable energy in pavement engineering and its integration with sustainable materials: A review paper

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Abstract. Pavement engineering that incorporates renewable energy sources and uses sustainable materials has emerged as a promising path toward achieving an environmentally friendly and sustainable transportation infrastructure. An inclusive review of renewable energy applications in pavement engineering and its integration with sustainable materials is presented in this paper. The article examines various renewable energy technologies and their potential integration into pavement construction, maintenance, and operation. The findings of this review contribute to advancing sustainable practices in the transportation infrastructure sector and provide valuable insights for researchers, policymakers, and practitioners.

Introduction

Eco-friendly and sustainable transportation infrastructure can be achieved through the incorporation of sustainable materials and the use of renewable energy sources. In pavement engineering, renewable energy refers to the incorporation of energy generation technologies that utilize renewable sources of energy to power various aspects of pavement systems. By integrating renewable energy solutions, pavement engineering can contribute to sustainable and environmentally friendly transportation infrastructure. The applications of renewable energy in pavement engineering include Solar Photovoltaic (PV), Piezoelectric Energy Harvesting, thermoelectric energy harvesting, Kinetic Energy Harvesting and Geothermal Systems.

Whereas, sustainable materials refer to those that are environmentally friendly and have a reduced impact on natural resources throughout their life cycle. These materials are designed to minimize energy consumption, emissions, and waste generation during their production, use, and disposal. Sustainable materials used in pavement engineering include recycled asphalt, porous asphalt, warm mix asphalt etc. The use of sustainable materials in pavement engineering promotes resource conservation, reduces environmental impacts, and contributes to the development of more sustainable transportation infrastructure.

The combination of renewable energy in pavement engineering, along with the integration of sustainable materials, holds great importance in establishing infrastructure systems that are sustainable, resilient, cost-effective, and environmentally friendly. The objective of this study is to provide a detailed investigation of the current state of renewable energy implementation in pavement engineering, as well as its integration with sustainable materials based on existing

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literature. The paper explores various renewable energy technologies and their potential for integration into pavement construction, maintenance, and operation processes.

Sustainable Materials in Pavement Engineering

Sustainable materials in pavement engineering refer to materials chosen and employed in the construction, maintenance, and rehabilitation of pavements, with the primary objective of minimizing environmental impact, preserving resources, and fostering long-term sustainability.

Yaro et al [1] provides a comprehensive exploration of the utilization of recycled waste materials and technologies in asphalt pavements, with a focus on environmental sustainability and low-carbon roads. The findings emphasize the significant environmental and economic benefits of utilizing recycled materials, including reduced reliance on virgin materials, energy savings, and lower carbon emissions. This study also illustrate that the incorporation of such materials improves the performance characteristics of asphalt pavements.

A study [2] was conducted to evaluate the performance of Asphalt Concrete using 60/70 pen asphalt and a modified binder with resin in hot mix asphalt for road pavement. The research explores the use of renewable resources as alternatives to petroleum-derived materials in bio asphalt production Results revealed that all mixtures showed similar values for optimum bitumen content, but higher percentages of resin resulted in improved stability of the asphalt mixtures.

Praticò et al [3] presents a comprehensive life cycle assessment (LCA) of pavement technologies, specifically hot mix asphalt (HMA) and warm mix asphalt (WMA), with a focus on incorporating recycled materials such as reclaimed asphalt pavements, crumb rubber, and waste plastics. The findings demonstrate the benefits of utilizing WMA and recycled materials in reducing energy consumption and environmental effects by minimizing the use of virgin resources. It also offer cleaner production processes and significant environmental and technical benefits, including reduced energy consumption and greenhouse gas emissions, improved compaction, longer paving periods, and enhanced worker safety.

Renewable Energy Technologies in Pavement Engineering

In pavement engineering, the adoption of renewable energy technologies enhances sustainability and boosts the efficiency of transportation infrastructure by integrating sustainable energy systems into roads. By harnessing renewable energy, transportation infrastructure can become more sustainable and efficient, contributing to a greener and more effective transportation network.

Research [4] focuses on concentrated photovoltaic panels (CPPs) for pavement applications as a clean and renewable energy source in transportation. The study presents a comprehensive analysis of the structural optimization and performance testing of CPPs, demonstrating their feasibility, durability, and economic viability. Mechanical and electrical performance tests reveal the panel's strength, wear resistance, light concentration performance, and power generation capabilities. The CPP system showcases significant economic benefits, with a high return on investment and cost recovery period. Furthermore, it contributes to environmental sustainability by reducing carbon emissions.

The article by Zhou et al. [5] explores the feasibility and performance of a pavement-solar energy system through experimental analysis. The study aims to integrate solar energy collection technology into pavement systems to generate electricity and enhance environmental sustainability (Fig. 1). The experimental results demonstrate that the pavement-solar energy system effectively produces electricity from solar radiation, indicating its potential as a renewable energy source. The study emphasizes the importance of optimizing system design and orientation to improve energy harvesting.

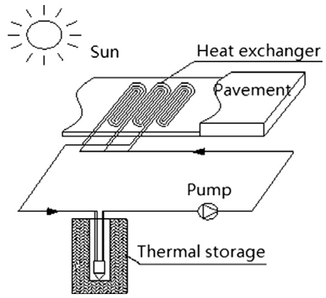

Figure 1 Harnessing solar energy through pavement infrastructure [5]

The study performed by Dunican [6] emphasizes the importance of diversifying solar power generation options in the construction sector to achieve a greener and more sustainable future. It argues that while rooftop solar solutions have become popular, alternative technologies such as transparent solar windows, solar shingles, and solar canopies offer additional opportunities to maximize renewable energy in buildings. Diversification provides benefits such as increased solar density, optimized space utilization, compliance with building codes, and design flexibility. By integrating solar technology into building materials, passive surfaces like windows can be utilized for energy production without compromising functionality.

Ma et al. [7] investigates the use of road pavements as solar energy generators in smart and sustainable cities, focusing on three pavement modules: pavement-integrated photovoltaic (PIPV), pavement-integrated solar thermal (PIST), and pavement-integrated photovoltaic thermal (PIPVT) modules (Fig. 2). PIPVT module achieves slightly higher electricity yield but lower heat yield compared to PIPV and PIST modules, with an average energy efficiency of 37.31%. All modules reduce the maximum asphalt average temperature, with PIPVT having the most significant effect, decreasing it by an average of 10.57°C. Additionally, they contribute to mitigating the urban heat island (UHI) effect, with PIPVT and PIST modules exhibiting the most and least influence, respectively.

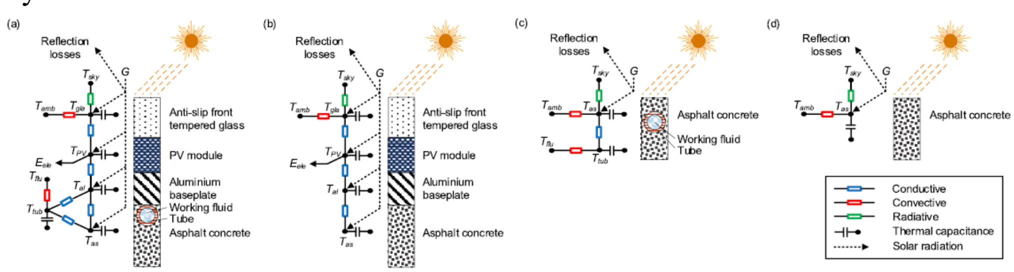

Figure 2 Thermal resistance networks of different solar energy harvesting pavements (a) PIPVT module; (b) PIPV module; (c) PIST module; (d) CP module [7]

Del Serrone et al. [8] explores the concept of utilizing photovoltaic (PV) road pavements to create low-carbon urban infrastructures. It emphasizes the importance of cool pavements in mitigating Urban Heat Islands (UHIs) and discusses the integration of PV panels into road surfaces to generate renewable energy. A case study in Rome exemplifies the potential of photovoltaic road infrastructures (Fig. 3), demonstrating their ability to generate electricity, maintain acceptable temperatures, and provide economic viability. Photovoltaic road pavements offer multiple benefits, including reduced energy consumption, enhanced microclimates, and reduced land use for solar installations.

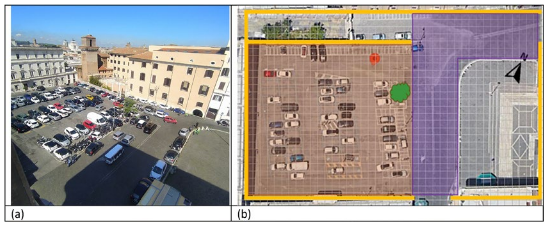

Figure 3 San Pietro in Vincula Square: (a) top view; (b) site map. [8]

Sumorek & Buczaj [9] performed the study to addresses the technological gap between automotive engineering and road infrastructure development by focusing on energy generation from road pavement. It evaluates the feasibility of capturing solar energy and converting it into usable electricity on the road surface, as well as harvesting mechanical vibrations energy from passing vehicles using piezoelectric transducers. The study confirms the significant potential of solar energy conversion and vibrations energy harvesting, with experimental results supporting the feasibility of converting mechanical vibrations energy into electrical energy (Fig. 4).

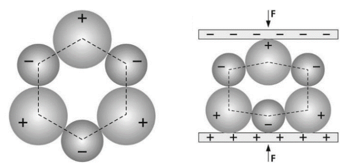
Figure 4 Mechanism of mechanical vibrations energy into electrical energy [9]

The article by Sun et al. [10] provides an in-depth exploration of green technologies for sustainable pavements, focusing on energy harvesting and permeable pavement systems. The article discussed the energy harvesting technologies including piezoelectric, solar, thermoelectric, and geothermal. Permeable pavement systems are highlighted for their ability to facilitate water infiltration, preventing urban flooding and reducing the urban heat island effect. Porous materials such as porous asphalt and concrete are examined, offering benefits like noise reduction and improved hydraulic conductivity.

Al-Qadami et al. [11] provide a systematic analysis of the existing literature on pavement geothermal energy harvesting technologies. Three main sectors are identified: piezoelectric transducer systems, thermoelectric generator systems (TEGs), and solar panel systems (Fig. 5). Piezoelectric transducer systems convert the mechanical stress from moving vehicles into electrical energy using embedded piezoelectric materials. Studies emphasize material selection, pavement design, and traffic characteristics' impact on energy generation, highlighting their potential in high-traffic areas. TEGs harness the temperature difference between the pavement surface and underlying layers to generate electricity. Research focuses on enhancing efficiency through material selection, module configuration, and optimization, indicating their integration into smart pavement systems. Solar panel systems effectively convert solar energy into electricity and can be embedded within or placed on pavement surfaces.

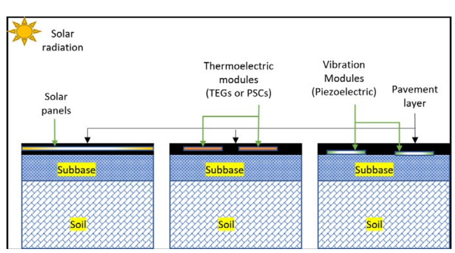

Figure 5 Pavement energy harvesting technologies [11]

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Razeman et al. [12] investigated solar pavements as a means of efficiently harnessing solar energy, emphasizing sustainable conductive materials like stainless steel, copper, and aluminum. Numerical simulations are employed to optimize parameters such as pipe material, depth, arrangement, spacing, and flow rate. The results highlight serpentine copper pipe as the most efficient configuration, achieving a heat efficiency rate of 32.22% and an outlet temperature of 327.35K (54.21°C). The study underscores the benefits of solar pavement technology, reduced reliance on fossil fuels, emissions reduction, and reliable electricity generation.

Tahami et al. [13] proposed an innovative approach to harvest energy from asphalt pavements using thermoelectric technology. The findings indicate that the temperature difference in the pavement can produce sufficient electrical energy, especially in areas with intense sunlight exposure and high traffic density. The thermoelectric system demonstrated the ability to generate sustainable energy without compromising pavement performance. The authors discussed the potential applications of this technology in existing infrastructures for renewable energy generation and environmental sustainability. However, challenges such as cost-effectiveness, scaling up, and long-term durability need to be addressed for commercialization and implementation.

Gholikhani et al [14] highlights the potential of utilizing roadway pavements as a renewable energy resource through the electromagnetic speed bump energy harvester (ESE) prototype. This innovative approach aims to capture kinetic energy from passing vehicles while regulating vehicle speed. The ESE prototype absorbs the deflection caused by vehicles passing over a speed bump and converts it into rotational energy using a revolving shaft and embedded generator. Laboratory experiments demonstrate its capability to generate an average power output of up to 3.21 kW under realistic traffic loading conditions. Steel and aluminum are identified as optimal materials for the ESE's top plate due to their favorable properties.

De Fazio et al [15] explored the potential of energy harvesting from various sources on roadways, including mechanical load, solar radiation, heat, and air movement, for the development of self-sustainable smart roads. It examines different technologies such as electromagnetism, piezoelectric and triboelectric harvesters, photovoltaic modules, thermoelectric solutions, and wind turbines optimized for low-speed winds generated by vehicles. The findings emphasize the environmental benefits and potential applications of energy harvesting in the transportation sector, such as autonomous driving, real-time road condition communication, self-powered lighting systems, and security sensors.

The investigation by Saleh et al. [16] focuses on the Hydronic Asphalt Pavement (HAP) system. The HAP system utilizes a network of pipes embedded in the asphalt pavement to remove or reject heat from the pavement using a circulating fluid. The study evaluates the efficiency of the HAP system in reducing pavement surface temperature and enhancing sustainability. The results show that the HAP system successfully lowered the temperature at a depth of 2.5 cm below the surface by approximately 10°C. However, the surface temperature reduction was not significant.

Johnsson [17] study focuses on making the Coastal Highway Route E39 carbon neutral and incorporating energy output facilities. The study explores the use of renewable thermal energy to prevent road surfaces from becoming slippery, considering the warming of sidewalk surfaces and the use of solar energy to melt snow and ice. The study suggests that the proposed hydronic pavement system, when combined with BTES, can enhance winter road maintenance and safety, particularly in regions with milder winters like Scandinavia.

Charlesworth et al. [18] explores the combination of ground source heat (GSH) and pervious paving systems (PPS) to create a sustainable drainage and renewable energy solution. GSH, obtained from the ground, is a renewable energy source that can efficiently heat and cool buildings. Pervious paving systems, such as block pavers, porous asphalt, concrete, and resin, are capable of attenuating storm surges, reducing water quantity, and improving water quality. The integration of GSH collectors with PPS allows for harnessing temperature differences within the ground.

The review paper [19] provides an overview of energy harvesting from roadways and its potential in combating the urban heat island effect. It explores various technologies, including electromagnetic, piezoelectric, thermoelectric, and solar panels, highlighting piezoelectric and thermoelectric systems as promising options. The study emphasizes the importance of hybrid systems that combine multiple energy sources for consistent power supply. Energy harvesting from roadways can reduce greenhouse gas emissions, power roadside applications, and provide electricity to roadside houses, presenting significant opportunities for sustainable energy generation. Table 1 provides a summary of literature references related to the application of renewable energy in pavement engineering.

Table 1 Application of Renewable Energy in Pavement Engineering

S. No	Reference from Literature	Application of Renewable Energy in pavement Engineering	Type of Study
1	Hu et al. [4]	Concentrated (converge sunlight) photovoltaic solar Pavement, (Concentrated photovoltaic panel (CPP) structure for pavement)	Laboratory model test and finite element numerical simulation
2	Zhou et al. [5]	Pavement-solar energy system	Experimental study
3	Ma et al. [7]	Solar energy harvesting pavements	Mathematical modeling and simulation conducted for pavement-integrated photovoltaic (PIPV) module, pavement integrated solar thermal (PIST) module, and pavement-integrated photovoltaic thermal (PIPVT) module.
4	Del Serrone et al. [8]	Utilizing photovoltaic (PV) road pavements is analyzed from the thermal and economic viewpoints	A microclimate simulation of San Pietro in Vincula Square in Rome is conducted using ENVI-Met software.
5	Sumorek & Buczaj [9]	Solar energy and vibrations energy	A combination of theoretical analysis and experimental testing
6	Sun et al. [10]	Energy harvesting technologies (Piezoelectric, solar, thermoelectric, and geothermal technologies) and permeable pavement systems	Literature review
7	Al-Qadami et al. [11]	Harvesting geothermal energy from roadway pavement (piezoelectric transducer systems, thermoelectric generator systems, and solar panel systems)	A systematic review and bibliometric analysis were conducted
8	Randriantsoa et al. [19]	Hybrid energy harvesting systems (combining piezoelectricity and thermoelectricity for pavement applications)	Bibliographic research
9	Razeman et al. [12]	Thermal energy harvesting road pavement	Numerical Simulation using ANSYS Workbench 19.2 (Fluent) and Solidworks 2020 for conducting optimization study.
10	Tahami et al. [13]	Thermoelectric generator system that utilizes the thermal gradients between the pavement surface and the soil below the pavement and converts it to electricity	Prototype testing and finite element analyses were conducted
11	Gholikhani et al. [14]	Electromagnetic speed bump energy harvester (ESE)	laboratory prototype tests and finite element analysis was conducted using software ABAQUS.
12	De Fazio et al. [11]	The study explores different technologies, including electromagnetism, piezoelectric and triboelectric harvesters, photovoltaic modules, thermoelectric solutions, and wind turbines	Literature review

Conclusion

This review paper has explored the significance of renewable energy in pavement engineering and its incorporation with sustainable materials. The utilization of renewable energy sources in pavement engineering has the potential to bring about substantial environmental and economic benefits. By integrating sustainable materials into the design, construction, and maintenance of pavements, the sustainability of the infrastructure can further enhance.

The adoption of renewable energy technologies such as solar, Piezoelectric Energy Harvesting, thermoelectric energy harvesting, Kinetic Energy Harvesting and Geothermal Systems can significantly decrease greenhouse gas emissions associated with energy consumption in pavement construction and operation. This not only helps combat climate change but also reduces reliance on fossil fuels and promotes energy independence.

Moreover, the addition of sustainable materials in pavement engineering has been discussed as a complementary approach to renewable energy utilization. Sustainable materials, including recycled aggregates, reclaimed asphalt pavement, and bio-based binders, offer opportunities to reduce the environmental impact of pavement construction by saving natural resources and reducing waste generation. These materials can also contribute to the circular economy by promoting recycling materials within the pavement engineering.

In conclusion, the integration of renewable energy in pavement engineering, coupled with the use of sustainable materials, holds great promise for achieving a more sustainable and resilient transportation infrastructure. This combination can contribute to a more environmentally friendly and cost-effective pavements.

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