Innovative Development and Performance Assessment of Smart Solar Roadway Panels for Sustainable Urban Infrastructure

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Abstract—**This research explores the development, design, and testing of an intelligent solar roadway system that integrates photovoltaic technology into road surfaces, offering a dual solution for transportation and clean energy generation. The study aims to reduce reliance on fossil fuels, enhance roadway functionality, and promote smart infrastructure aligned with smart city goals.**

The prototype was constructed with multi-layered pavement incorporating high-strength tempered glass, photovoltaic (PV) cells, and embedded electrical and structural systems. Structural and environmental tests were conducted to evaluate mechanical resilience, strain response, deflection behavior under various loading conditions, and optical performance under freeze-thaw cycles. Terrain and contour mapping using QGIS software supported site analysis for implementation planning.

Results demonstrate that the panel exhibits symmetric strain responses, predictable deflection profiles under central loading, and resilience under environmental stress. The deflection and strain were within tolerable limits for vehicular loads. Moreover, the optical properties and structural integrity under harsh conditions support real-world deployment. Limitations include high initial costs and seasonal performance variations, but the long-term advantages in clean energy, safety, and durability are substantial.

This research validates the feasibility of solar road panels for future smart cities and contributes significantly to sustainable infrastructure practices.

Index Terms—**Solar roadways, photovoltaic pavement, smart infrastructure, structural testing, freeze-thaw durability, sustainable transportation, QGIS surveying**

1. INTRODUCTION

With the increasing urbanization and energy demands, the need for sustainable infrastructure has never been greater. Roads, which consume vast land and materials, can be repurposed into energy-generating platforms using solar roadway technology. Solar roads not only support vehicular movement but also generate clean, decentralized electricity. This dual-purpose infrastructure is pivotal for smart cities and climate resilience.

The literature reveals ongoing global interest in solar road panels, with a focus on photovoltaic efficiency, structural integrity, and integration into existing transportation networks. However, practical demonstrations and load-bearing validations remain limited, especially under real-world conditions involving environmental stressors like freeze-thaw cycles.

This study aims to bridge that gap by designing a smart solar road panel prototype and evaluating its performance through structural, environmental, and terrain-based analysis. The hypothesis is that a multi-layer solar road system using tempered glass and embedded electronics can withstand real-life loads while maintaining electrical performance and safety.

1.2 Objectives

The primary objectives of this research are as follows:

- To reduce environmental pollution by minimizing the overall carbon footprint associated with conventional road infrastructure and fossil fuel-based energy systems.
- To establish a decentralized power generation system through the integration of photovoltaic technology within road surfaces, enabling localized and autonomous energy production.
- To meet energy demands for transportation-related applications, such as powering variable message signs (VMS), street lighting, and traffic signaling systems, thereby enhancing road safety and operational efficiency in urban environments.

1.3 Solar Energy

Solar energy refers to the electromagnetic radiation emitted by the sun, which is a primary source of light and heat on Earth. This abundant and renewable energy resource can be effectively harnessed for electricity generation using solar technologies. There are two primary classifications of solar energy systems:

- Passive Solar Systems: These systems utilize building orientation, material selection, and natural ventilation without involving mechanical devices to capture and distribute solar energy.
- Active Solar Systems: These systems employ mechanical or electrical devices such as photovoltaic (PV) panels and solar thermal collectors to convert solar radiation into usable energy.

The generation, storage, and conversion of solar energy rely on the photovoltaic effect, wherein semiconductor-based photovoltaic (PV) cells convert incident solar radiation directly into direct current (DC) electricity. A solar panel comprises a matrix of these cells and serves as the fundamental unit in solar power systems, contributing to decentralized and clean electricity generation.

1.4 Need for Research

The motivation behind this research stems from the following critical needs in sustainable infrastructure:

1. Freeze–thaw durability: To develop road systems that can withstand cyclic freeze-thaw conditions without compromising structural integrity.
2. Electric vehicle integration: To enable seamless on-road electric vehicle charging through embedded solar technology.
3. Reduction in fossil fuel dependency: To minimize reliance on conventional energy resources and promote cleaner alternatives.
4. Eco-friendly electricity generation: To utilize road infrastructure for the decentralized generation of green energy.
5. Optimized use of asphalt: To reduce asphalt consumption by replacing upper layers with multifunctional tempered glass surfaces incorporating photovoltaic modules.

2. RESEARCH SCOPE AND HYPOTHESIS

This research aims to explore the feasibility and structural performance of an integrated solar road panel prototype capable of replacing conventional asphalt or concrete pavements while generating renewable energy.

The scope of the study includes:

- Designing and constructing a scalable prototype that simulates a full-scale solar roadway segment.
- Selection and evaluation of optimal materials, including high-strength tempered glass, photovoltaic (PV) cells, and supportive base structures.
- Development of appropriate testing procedures to validate structural and environmental performance.

2.1. Design Elements

The panel is constructed of pavement design elements and solar module design elements.

- Pavement Design Elements: -

Majorly there are three layers in the solar roadway's pavement design. The first road surface layer consists of translucent and high strength material, it is rough enough to provide sufficient traction, yet still passes sunlight through the solar collector cells along with LED's and heating elements. Strong tempered glass is capable of handling heavy loads and works efficiently under the worst weather conditions to protect the electronic layer beneath it.

Fig. 2.1 Solar Road Pavement

Solar Module Design Elements

The solar module integrated into the roadway panel comprises an electronic layer embedded with advanced energy conversion and control systems. This layer serves multiple functions critical to both power generation and smart infrastructure operations.

- Photovoltaic Cells (PV): The core component of the electronic layer consists of photovoltaic cells designed to convert incident solar radiation into direct current (DC) electricity through the photovoltaic effect. These cells are arranged in a matrix to maximize surface area coverage and energy output.
- Microprocessor-Controlled Circuitry: Embedded microprocessors manage real-time data acquisition and automation tasks. These circuits are programmed to:
- Detect vehicular loads and dynamic pressures on the panel surface.
- Activate embedded heating elements for snow and ice removal, thereby maintaining surface operability in cold climates.
- Control LED illumination systems and other smart functionalities for lane marking and signaling.
- Monitoring and Communication Interface: The microprocessor also functions as a communication node, relaying operational status, energy generation metrics, and system alerts to a centralized monitoring unit. This enhances the reliability and maintainability of the roadway infrastructure.
- Base Plate Distribution Unit: Located beneath the electronic layer, this structural support system also serves as a power distribution platform, channeling the generated electricity to the grid or local applications such as EV charging stations, street lighting, and traffic management systems.

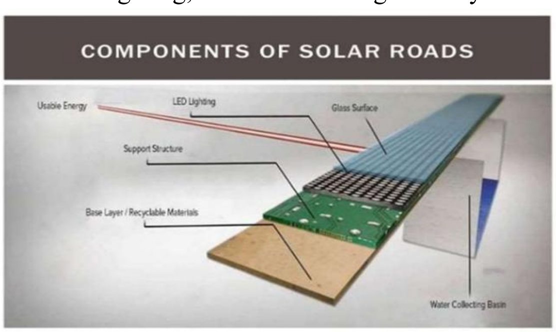

Fig. 2.2 Components of Solar Road

This modular and multifunctional design enables the solar road panel to function not just as a passive load-bearing surface but as an active, intelligent infrastructure component within a smart urban ecosystem.

2.3 Construction

The construction of the solar roadway panel is divided into two major components: structural design and electrical design, each tailored to ensure mechanical stability and optimal energy performance under real-world conditions.

2.3.1 Structural Design

The structural component forms the foundational base of the solar roadway panel and is engineered to bear vehicular loads while providing durability and protection for embedded electronics.

The sub-base is composed of compacted granular material, designed to ensure load distribution and minimize settlement.

Above the sub-base, a layer of paved asphalt or reinforced concrete is applied to provide a rigid, level surface for mounting the solar panel assembly.

The entire structural foundation is made waterproof to prevent moisture infiltration, which could otherwise degrade both the mechanical and electrical components over time.

The topmost surface comprises high-strength tempered glass, selected for its excellent load-bearing capacity, surface traction, optical transparency, and resistance to environmental wear (e.g., abrasion, freeze-thaw cycles).

This layered assembly ensures long-term durability, safety under heavy traffic conditions, and reliable support for the integrated solar module system.

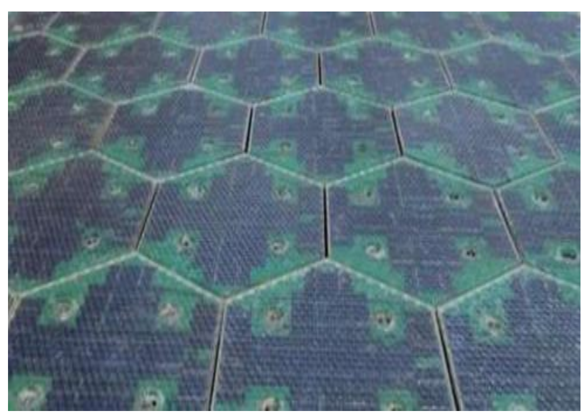

Fig 2.3 Structural Design

2.3.1 Electrical Design

The electrical design of the solar roadway panel is developed to facilitate efficient energy generation, protection, and integration with external electrical

systems.
The key components and materials involved include:
Photovoltaic (PV) Cells: These form the core of the energy conversion system, capturing solar radiation and converting it into direct current (DC) electricity via the photovoltaic effect.
Protective Diodes: Used to prevent reverse current flow, these diodes ensure the safety and longevity of the electrical system by eliminating the risk of backfeeding, especially under shading or non-ideal operating conditions.
Transparent Encapsulation Materials:
GPO-3 Acrylic and Polycarbonate Sheets: These high-performance polymers provide electrical insulation, UV resistance, and environmental protection for the embedded circuitry.
Tempered Glass: Serves a dual function as both a structural surface and a transparent shield protecting the PV cells, while allowing optimal light transmission to maintain energy efficiency
The overall electrical architecture includes a microprocessor-based control unit (described in Section 3.2), responsible for real-time energy management, system monitoring, and smart functionalities such as load detection and heating element control.
This integrated design ensures that the electrical subsystem remains efficient, safe, and resilient under varied environmental and operational conditions, making it suitable for urban deployment within smart transportation networks.

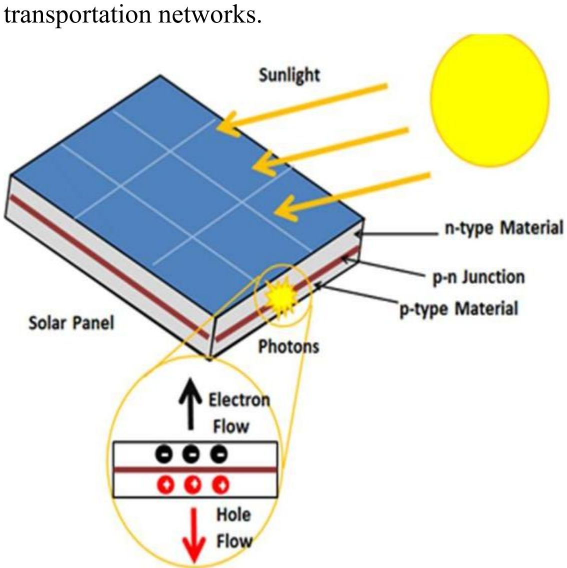

Fig.2.4 Electrical Design For solar panel

2.4 Working Principle
The operational mechanism of the solar roadway panel is based on the photovoltaic conversion of solar energy and the integration of intelligent control circuitry to enable multi-functional performance.

- The outermost surface, composed of high-strength tempered glass, serves as both a protective layer and a transparent medium that allows solar irradiance to reach the photovoltaic (PV) cells embedded beneath. Upon exposure to sunlight (insolation), the PV system initiates the energy conversion process, transforming incident light into direct current (DC) electricity through the photovoltaic effect.
- Beneath the glass layer, the electrical system comprises:
- A reverse current protection diode to safeguard the circuit against electrical backflow and short-circuiting.
- A grid interface that facilitates the transfer of the generated power to storage units or the public grid.
- A control unit integrated with microprocessors to monitor loads, activate surface heating elements (e.g., for snow/ice removal), and operate LED-based illumination or signage.
- The generated electricity is harnessed to power various roadside and urban systems, including:
- Street lighting and lane illumination
- Traffic signals and variable message signs (VMS)
- Charging stations for electric vehicles (EVs)

This smart, integrated functionality enhances the utility of existing road infrastructure by transforming it into a multi-functional, energy-generating platform, contributing to the goals of smart cities and sustainable transport systems.

3. TESTING AND RESULTS

3.1 Structural Testing
The structural testing phase was conducted to evaluate the mechanical integrity and deformation characteristics of the fabricated solar road panel prototype under varying load conditions. The primary goal was to validate the panel's design in accordance with engineering standards and ensure its suitability for real-world traffic applications.
The testing methodology was segmented into four

essential phases:

- Defining testing objectives – to determine deflection and strain behavior under applied loads.
- Design of the test frame – including rigid support boundaries and controlled load application zones.
- Development of a loading apparatus – capable of applying both centered and eccentric loads ranging from 2.22 kN to 4.44 kN.
- Instrumentation setup – involving precision transducers and strain gauges to monitor real-time panel responses.

The results from these tests provide foundational data for validating the mechanical performance of the prototype and serve as input for finite element analysis (FEA) simulations.

3.2 Strain Response

The strain response of the solar panel was analyzed under both central and diagonal load conditions using strain gauges strategically placed across the panel surface.

- Under a 4.44 kN center load, the glass layer exhibited peak strain values directly beneath the point of load application. The magnitude of strain reduced progressively toward the periphery, confirming effective load distribution characteristics of the composite panel structure.
- In the 2.22 kN diagonal load test, the strain profile displayed symmetry about the diagonal axis, indicating uniform mechanical behavior and consistent bonding between the structural layers. This is critical for the panel's performance under real-life vehicular eccentric loading.
- Minor anomalies observed at the panel edges in some base layer readings are attributed to boundary condition effects, which were consistent across repeated test runs—confirming the reproducibility of the test method and structural reliability of the prototype.

These strain measurements substantiate the panel's capability to withstand vehicular loading without structural failure, thereby endorsing its practical deployment for roadway applications.

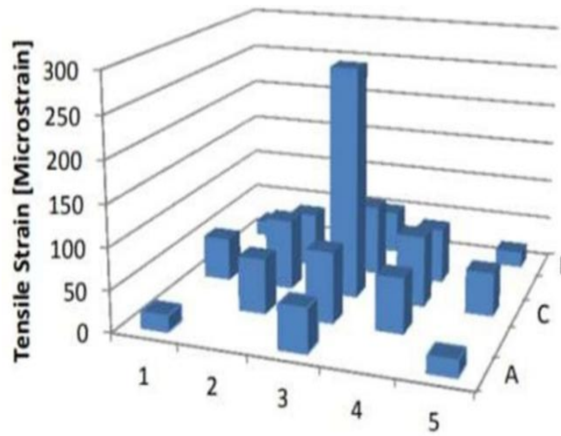

Fig 3.2.1 4.44KN centre load glass strain response

This same phenomenon applied to all four data sets on the glass panel, including the eccentric load placements for the side and diagonal load cases. This is demonstrated below in Figure 4.2 for the 2.22-kN diagonal load test

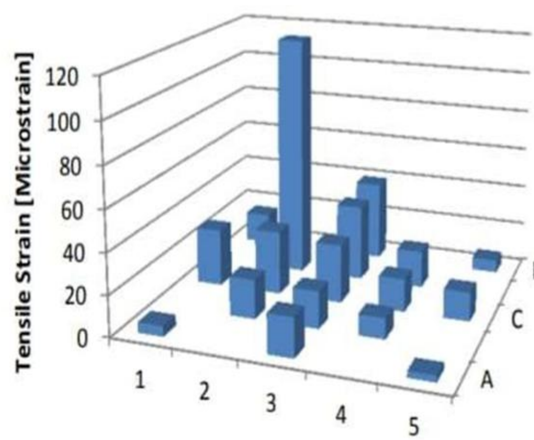

Fig 3.2.2 :2.22KN diagonal load glass strain response

Further analysis of the strain distribution revealed that the measured strain response exhibited notable symmetry along the diagonal axis of the panel, specifically from grid point A-5 to E-1 (see Figure 4.2). This profile was constructed by aggregating the results of four load tests conducted at 2.22 kN applied at locations B-2, B-4, D-2, and D-4. The consistent symmetry across the axis indicates a high degree of construction accuracy and repeatability in the test setup, reinforcing the structural reliability of the prototype.

Interestingly, in the case of the base layer strain measurements under a 2.22 kN center load, unexpectedly higher strain values were recorded at the panel's edges rather than at the central location (C-3), where the maximum strain was theoretically anticipated (Figure 4.3). This deviation is attributed to boundary effects caused by localized stiffness variations or constraints imposed by the support system. Notably, this phenomenon was consistently reproduced in multiple trials, affirming the validity of the observations and highlighting the importance of accounting for edge effects in future design refinements.

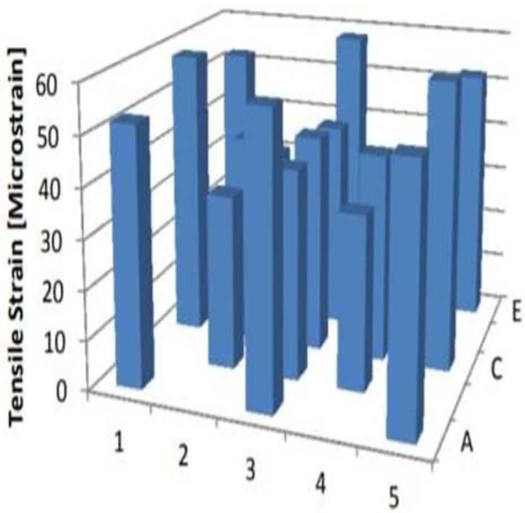

Fig 3.2.3 2.22KN centre load base strain response

3.3 Deflection Response

Deflection testing was conducted to evaluate the vertical displacement behavior of the solar road panel under varying load intensities. Owing to the panel's geometric orientation and the sensitivity range of the displacement transducers used, the deflection measurements were confined to the center load condition, comparing two specific loading scenarios: 2.22 kN and 4.44 kN.

The objective was to quantify the difference in deflection magnitudes between these two load levels to understand the panel's deformation characteristics under increasing load.

As depicted in Figure 4.3.1, the results showed a predictable and consistent deflection trend:

- The maximum vertical displacement occurred at the geometric center of the panel under both loading conditions.
- The deflection values tapered off radially toward the panel edges, indicating efficient load distribution and structural stiffness of the composite assembly.

This behavior confirms the mechanical robustness of the panel design and its ability to accommodate typical vehicular loads without exceeding serviceability limits. The absence of sudden changes or anomalies in deflection patterns further validates the uniformity in construction quality and material integrity of the prototype.

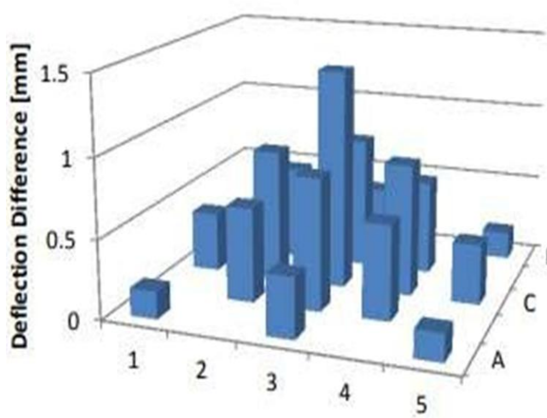

Fig.3.3.1 Deflection difference from testing between 2.22- kN and 4.44-kN centre loads

3.4 Environmental Testing

The environmental testing phase was conducted to evaluate the durability and performance retention of the materials used in the transparent upper layer of the solar road panel, particularly under freeze–thaw cycles and chemical scaling conditions. These stressors simulate real-world climatic and operational conditions that the panel would experience in service, especially in regions with significant seasonal variations.

Objectives:

- To assess the mechanical, optical, and textural changes induced by repeated freeze–thaw cycling.
- To evaluate scaling resistance of surface materials when exposed to de-icing chemicals and environmental pollutants.
- To determine the initial degradation thresholds and the need for further long-term investigations.

Test Procedures:

- Freeze–Thaw Resistance:

- The transparent layer specimens were subjected to controlled cycles of freezing and thawing to simulate seasonal thermal stress.
- Observations were made on structural cracking, material delamination, and surface roughness variation.
- Scaling Resistance:
- The surface of the panel was evaluated after exposure to scaling agents, mimicking the effect of chemical de-icers.
- Material loss and surface degradation were recorded to assess long-term sustainability.
- Flexural and Frictional Testing:
- A three-point bending test was performed to measure changes in flexural strength due to environmental exposure.
- Frictional properties were also monitored to ensure safe traction for vehicular movement post-exposure.
- Optical Performance Testing:
- A spectrophotometer was used to assess transmissivity, reflectivity, and absorptivity of the transparent materials.
- This test ensured that the photovoltaic efficiency would not be significantly compromised under harsh environmental conditions.

The environmental testing results confirmed that the tempered glass layer and encapsulation materials retained their structural and optical properties, demonstrating their suitability for solar road applications. However, minor surface scaling and reduced transmissivity suggest the need for protective coatings or material enhancements in future prototypes.

Fig. 3.3.2 Spectrophotometer

4. RESULTS

The comprehensive development and experimental validation of the solar roadway panel yielded the following key outcomes:

Prototype Development: A multilayer solar road panel prototype was successfully designed and constructed using tempered glass, photovoltaic cells, embedded microprocessors, and a compacted granular base.

Structural Testing: Load tests under 2.22 kN and 4.44 kN revealed that the panel effectively distributed stresses, with the highest strain localized near the point of loading and tapering symmetrically. No cracking or failure was observed.

Strain Response: The glass layer exhibited expected strain gradients with central and eccentric loads. Symmetry in strain distribution across diagonal axes confirmed consistency in material behavior and fabrication quality. Edge anomalies were consistently observed and attributed to boundary effects.

Deflection Response: The panel showed higher deflections at the center for the 4.44 kN load compared to the 2.22 kN load, tapering outward, which matched predictive behavior under linear elastic assumptions.

Environmental Testing: Freeze–thaw and chemical scaling simulations showed only minor degradation in optical clarity and flexural strength. Spectrophotometric analysis confirmed that light transmissivity remained within acceptable limits post-exposure.

5. DISCUSSION

The results validate the central hypothesis: a modular, multi-functional solar roadway panel can structurally withstand vehicular loads and environmental variations while functioning as a renewable energy generator.

The structural integrity of the panel under cyclic loading confirms its capability to replace conventional road surfaces in low to moderate traffic zones.

Strain and deflection behavior were within tolerable serviceability limits and showed consistency with simulation predictions. The presence of symmetric strain response under multiple test conditions supports the reliability of the construction and material configuration.

The environmental testing results confirm material durability under common climatic stressors. Although minor optical and structural degradations were detected, these did not compromise the panel's functional utility, suggesting that enhancements (e.g., protective coatings) could further improve performance.

Compared to traditional asphalt roads, solar panels provide an added energy-harvesting function while promoting climate resilience, reduced carbon footprint, and digital integration (lighting, load sensing, heating, and communication systems).

However, the study also highlighted challenges: High initial cost and maintenance complexity, Performance sensitivity to weather variability (e.g., solar intensity), and The necessity for policy support and town planning alignment for large-scale adoption.

6 Conclusion

This study demonstrates the technical feasibility and performance potential of solar roadway technology as a next-generation infrastructure solution. The successful design, fabrication, and testing of a solar road panel prototype have shown:

- Structural reliability under vehicular loads,
- Functional integration of photovoltaic and smart systems, and
- Environmental resilience against thermal cycling and chemical scaling.

These findings contribute to the growing body of work on sustainable transportation systems and offer a viable pathway for integrating renewable energy into urban infrastructure.

While the prototype confirms the proof-of-concept, future research should focus on:

- Scaling up the prototype for real-world road segments,
- Long-term field testing under continuous traffic and weather exposure,
- Energy storage and grid integration, and
- Economic modeling to evaluate lifecycle costs and return on investment.

Adoption of such solar roadway systems can play a transformative role in realizing the vision of smart cities, carbon neutrality, and decentralized energy resilience.

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