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Review Article



## Evaluating Spider Web Pavement versus Conventional Pavement for Sustainable Road Infrastructure

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### Abstract

Road pavement plays a critical role in ensuring the functionality and sustainability of transportation infrastructure, particularly under increasing traffic loads and challenging subgrade conditions. Conventional pavement systems, although widely used, often exhibit performance limitations, such as deformation and differential settlement, when applied to weak soils. This study aims to compare the Spider Web Pavement (slab-on-pile system) with conventional pavement systems in terms of structural performance, technical characteristics, and economic efficiency. A descriptive-comparative methodology based on a systematic literature review was employed to analyze key parameters, including load distribution, pavement thickness, construction complexity, maintenance requirements, and service life. The results indicate that the Spider Web Pavement system provides superior structural performance by efficiently transferring loads to deeper soil layers, significantly reducing subgrade stress and minimizing settlement. It also demonstrates greater resistance to deformation and a longer service life than conventional pavements. However, these advantages are associated with greater construction complexity and higher initial costs. In contrast, conventional pavements offer simpler construction processes and lower upfront investment but require higher maintenance and exhibit shorter service life, particularly under weak subgrade conditions. The findings suggest that while conventional pavements remain suitable for stable soils and cost-sensitive projects, Spider Web Pavement systems offer a more sustainable and cost-effective solution in the long term, especially in geotechnically challenging environments. The study highlights the importance of adopting a life-cycle and performance-based approach in selecting appropriate pavement systems for sustainable road infrastructure development.



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## 1. Introduction

Road infrastructure constitutes a critical backbone of modern transportation systems, playing a decisive role in facilitating economic growth, enhancing regional connectivity, and improving accessibility across urban and rural landscapes. As global mobility demand continues to increase, driven by rapid urbanization and industrial expansion, pavement systems are subjected to escalating traffic volumes and heavier axle loads. Consequently, ensuring structural reliability, long-term durability, and environmental sustainability has become a central concern in pavement engineering research and practice (Badran et al., 2023; Guo et al., 2025).

Conventional pavement systems, comprising flexible (asphalt-based) and rigid (cement-based) structures, have long dominated roadway construction due to their

well-established design methodologies, standardized construction procedures, and relatively cost-effective implementation under typical subgrade conditions (Darmawan & Wibowo, 2020; Dewi, 2023). However, despite their widespread application, these systems exhibit inherent limitations when exposed to challenging geotechnical environments. Common pavement distresses, including cracking, rutting, and differential settlement, are frequently observed, particularly when pavements are constructed over weak, compressible, or moisture-sensitive subgrades (Rosyidi, 2021). Such deficiencies not only compromise structural performance but also increase maintenance requirements and life-cycle costs.

In response to these challenges, traditional engineering approaches often rely on increasing pavement thickness or implementing subgrade

improvement techniques, such as soil stabilization and compaction enhancement. While these methods can provide temporary performance improvements, they are not always structurally efficient or economically viable, especially in regions characterized by persistently poor soil conditions. Furthermore, these approaches may result in increased material consumption and environmental burden, contradicting the growing emphasis on sustainable infrastructure development (Firoozi & Firoozi, 2023; Barbhuiya et al., 2025).

The global shift toward sustainability has significantly influenced pavement engineering practices, encouraging the adoption of innovative materials and structural systems that minimize environmental impact while maintaining or enhancing performance. Recent studies highlight the effectiveness of sustainable pavement technologies, including reclaimed asphalt pavement (RAP), warm-mix asphalt (WMA), recycled aggregates, and industrial by-products, in reducing greenhouse gas emissions, conserving natural resources, and improving life-cycle performance (Badran et al., 2023; Wu et al., 2025; Huang, 2025). Life-cycle assessment (LCA) frameworks further demonstrate that integrating such materials can significantly reduce environmental burdens compared to conventional pavement systems (Hasheminezhad et al., 2024; Hu et al., 2019). Nevertheless, material-based innovations alone may not fully address the structural challenges posed by weak subgrade conditions.

To overcome these limitations, alternative structural concepts have been developed, among which the Spider Web Pavement system, also known as the slab-on-pile approach, has gained increasing attention. This method utilizes a reinforced concrete slab supported by piles or anchors to transfer traffic loads to deeper, more competent soil layers, thereby reducing stress concentrations in the subgrade and minimizing differential settlement. Similar concepts, such as nailed slab systems, have also been explored, demonstrating improved load distribution and structural stability in soft soil environments (Fitriyani et al., 2023). These advanced systems represent a paradigm shift from traditional layered pavement design toward integrated structural-geotechnical solutions.

Despite their technical advantages, pile-supported pavement systems are associated with increased construction complexity, longer execution times, and higher initial capital costs. These factors often limit their widespread adoption, particularly in developing regions where budget constraints and construction simplicity remain key considerations. Moreover, uncertainties regarding long-term performance, cost-effectiveness, and compatibility with existing infrastructure systems continue to pose challenges for large-scale implementation (Guo et al., 2025; Naik et al., 2024).

Given these considerations, there is a growing need for comprehensive comparative studies that evaluate both conventional and innovative pavement systems

across multiple dimensions, including structural performance, technical feasibility, economic efficiency, and environmental sustainability. Previous research has emphasized the importance of life-cycle cost analysis and performance-based evaluation frameworks in supporting informed decision-making for pavement design and management (Knott et al., 2019; Styer et al., 2024). Such analyses are essential to bridge the gap between theoretical advancements and practical engineering applications, particularly in the context of sustainable infrastructure development.

Against this backdrop, the present study aims to conduct a systematic and integrative comparison between the Spider Web Pavement system and conventional pavement approaches. The analysis focuses on three key dimensions: (i) structural performance under varying subgrade conditions and traffic loads, (ii) technical and construction-related considerations, and (iii) economic implications, including initial investment and life-cycle costs. By synthesizing insights from recent literature and comparative evaluation, this study seeks to provide evidence-based guidance for engineers, planners, and policymakers in selecting appropriate pavement solutions tailored to site-specific conditions.

Ultimately, this study contributes to the broader discourse on sustainable road infrastructure by highlighting the potential of innovative pavement systems to enhance structural resilience, optimize resource utilization, and support long-term environmental and economic sustainability.

## 2. Literature Review

The development of sustainable and high-performance pavement systems has become a central theme in contemporary transportation engineering, driven by increasing traffic demand, environmental concerns, and the need for long-term infrastructure resilience. Existing literature can be broadly categorized into three interrelated domains: (i) conventional pavement systems and their limitations, (ii) sustainable materials and innovations in pavement engineering, and (iii) advanced structural systems such as pile-supported or slab-based pavements. Synthesizing these domains provides a clear foundation for identifying the research gap this study addresses.

### 2.1 Conventional Pavement Systems and Performance Limitations

Conventional pavement systems, including flexible and rigid pavements, have been extensively studied and widely implemented due to their established design procedures and cost efficiency. Flexible pavements rely on layered systems to distribute loads, whereas rigid pavements utilize high-stiffness concrete slabs to resist deformation. Comparative studies indicate that each system has distinct advantages depending on traffic

loading, material availability, and environmental conditions (Darmawan & Wibowo, 2020; Dewi, 2023).

However, the performance of conventional pavements is highly dependent on subgrade conditions. Weak or soft soils significantly reduce load-bearing capacity, leading to common distress mechanisms such as rutting, cracking, and differential settlement (Rosyidi, 2021). These issues often necessitate frequent maintenance and rehabilitation, thereby increasing life-cycle costs and reducing overall service life.

To mitigate such problems, traditional approaches include increasing pavement thickness or improving subgrade properties through stabilization techniques. While effective to some extent, these methods are material-intensive and may not provide optimal long-term performance, particularly in regions with persistent geotechnical challenges. This limitation highlights the need for alternative structural solutions that can better accommodate weak subgrade conditions.

## **2.2 Sustainable Materials and Pavement Innovations**

In parallel with structural challenges, environmental sustainability has emerged as a critical consideration in pavement engineering. The construction and maintenance of road infrastructure contribute significantly to resource depletion, energy consumption, and greenhouse gas emissions. Consequently, recent research has focused on integrating sustainable materials and technologies into pavement systems.

A growing body of literature demonstrates the potential of recycled and low-carbon materials, such as reclaimed asphalt pavement (RAP), recycled concrete aggregates, warm-mix asphalt (WMA), and industrial by-products, to reduce environmental impacts while maintaining acceptable mechanical performance (Badran et al., 2023; Firoozi & Firoozi, 2023). These materials not only reduce reliance on virgin resources but also support circular-economy principles by reusing waste products.

Advanced studies further highlight the role of innovative binders and composite materials in improving pavement durability and reducing carbon footprints (Wu et al., 2025; Huang, 2025). Life-cycle assessment (LCA) has been widely applied to evaluate the environmental and economic performance of these technologies, consistently showing that sustainable materials can significantly lower emissions and energy consumption over the pavement life cycle (Hasheminezhad et al., 2024; Hu et al., 2019).

Despite these advancements, most studies primarily focus on material-level innovations, with limited attention to structural system redesign, particularly in addressing geotechnical constraints such as weak subgrades. This indicates a critical gap in integrating sustainability with structural performance enhancement.

## **2.3 Advanced Structural Systems: Slab-on-Pile and Alternative Pavements**

To address the limitations of conventional pavement systems on weak soils, researchers have explored alternative pavement structures that enhance load transfer. One such approach is the slab-on-pile system, commonly referred to as Spider Web Pavement. This system utilizes a reinforced concrete slab supported by piles or anchors to transfer loads to deeper, more competent soil layers, thereby reducing stress on the subgrade and minimizing differential settlement.

Similar structural concepts, such as nailed slab pavements, have also been investigated as viable alternatives. Fitriyani et al. (2023) demonstrate that these systems can significantly improve structural stability and reduce deformation under heavy traffic loads, particularly in soft soil conditions.

These advanced systems represent a shift from traditional layered design toward integrated structural-geotechnical solutions. However, their adoption is often constrained by higher initial costs, increased construction complexity, and the need for specialized equipment. Additionally, there remains limited empirical evidence comparing their long-term economic performance with conventional pavements.

## **2.4 Economic and Life-Cycle Considerations in Pavement Design**

Economic evaluation is a critical component in pavement selection, as infrastructure projects must balance performance with budget constraints. Conventional pavements generally offer lower initial construction costs, making them attractive for short-term projects. However, their higher maintenance requirements can lead to increased costs over time (Darmawan & Wibowo, 2020).

In contrast, innovative pavement systems and sustainable materials often require a higher upfront investment but offer a longer service life and lower maintenance costs. Life-cycle cost analysis (LCCA) has been widely recommended as a comprehensive tool for evaluating such trade-offs, enabling decision-makers to consider both short-term and long-term economic impacts (Knott et al., 2019; Styer et al., 2024).

Furthermore, recent studies emphasize that integrating sustainability into pavement design requires a holistic approach that considers structural performance, environmental impact, and economic efficiency simultaneously (Guo et al., 2025; Barbhuiya et al., 2025).

Although extensive research has been conducted on conventional pavements, sustainable materials, and alternative structural systems, several critical gaps remain in the lack of integrated comparison between conventional pavement systems and advanced structural solutions such as Spider Web Pavement. Limited focus on structural-economic trade-offs,

particularly in the context of weak subgrade conditions. Also, Insufficient alignment between sustainability and structural innovation, as most studies emphasize material improvements rather than system-level design.

Addressing these gaps is essential for advancing sustainable pavement engineering. Therefore, this study aims to provide a comprehensive comparative evaluation of Spider Web Pavement and conventional pavement systems, focusing on structural performance, technical feasibility, and economic efficiency. By doing so, the research helps bridge the gap between theoretical innovation and practical implementation, supporting more informed and sustainable infrastructure decision-making.

### 3. Materials and Methods

This study employs a descriptive-comparative research design to systematically evaluate the performance of Spider Web Pavement (slab-on-pile system) relative to conventional pavement systems, including both flexible and rigid pavements. The approach integrates qualitative and quantitative perspectives to ensure a comprehensive assessment of structural behavior, technical feasibility, and economic performance. By combining descriptive explanation with comparative evaluation, the methodology is designed to provide a clear and rigorous basis for identifying the strengths and limitations of each pavement system, in line with the study's objective of supporting sustainable infrastructure decision-making.

The research adopts a literature-based analytical approach, drawing on validated academic sources published between 2018 and 2025. These sources include peer-reviewed journal articles, technical guidelines, and prior studies related to pavement engineering, sustainable materials, and geotechnical performance. The analysis begins with a descriptive synthesis of each pavement system, focusing on its fundamental design principles, load-transfer mechanisms, and applicability across different subgrade conditions. This is followed by a comparative analysis that evaluates their relative performance using standardized parameters, ensuring consistency and analytical depth across all aspects of the study.

The data used in this research are entirely secondary, obtained through a systematic review of relevant literature. The selection of sources prioritizes academic credibility, recency, and direct relevance to the research objectives. The reviewed materials emphasize three main domains: structural performance of pavement systems, advancements in sustainable pavement technologies, and economic considerations, including life-cycle cost implications. This structured selection process ensures that the analysis is grounded in reliable, up-to-date knowledge in pavement engineering.

To facilitate a robust comparison, the study defines a set of evaluation parameters grouped into three principal categories: structural, technical, and economic aspects. Structural parameters include load distribution mechanisms, pavement thickness, subgrade bearing capacity requirements, and resistance to deformation and differential settlement. Technical parameters encompass construction complexity, duration, equipment requirements, and adaptability to varying geotechnical conditions. Economic parameters focus on initial construction costs, maintenance costs over the service life, design life expectancy, and overall life-cycle cost efficiency. These parameters are selected based on their relevance to both engineering performance and sustainability considerations.

The data analysis process is conducted through a structured sequence of steps. First, the literature is classified by pavement type, structural system, and subgrade condition. Second, key variables are standardized to enable direct comparison between Spider Web Pavement and conventional systems. Third, a comparative evaluation is conducted across all defined parameters to identify performance differences. The results are then synthesized into a comparative framework that highlights the relative advantages and limitations of each method. Finally, a critical interpretation is performed to relate the findings to broader sustainability objectives, including durability, resource efficiency, and long-term economic viability.

The research process follows a logical workflow, beginning with problem identification related to pavement performance on weak subgrades, followed by literature review and data collection, parameter selection, comparative analysis, and concluding with synthesis and interpretation of findings. While the study is limited to a literature-based analysis and does not include primary data or experimental validation, the use of diverse, high-quality sources enhances the reliability and relevance of its conclusions. This methodological framework provides a systematic and integrative basis for evaluating alternative pavement systems and supports informed decision-making in the development of sustainable road infrastructure.

### 4. Results

A critical review of prior studies on conventional pavement systems and slab-on-pile systems (Spider Web Pavement) reveals that both approaches exhibit fundamentally different performance characteristics, particularly under weak subgrade conditions. Conventional pavements are generally effective when constructed on stable, well-compacted soils; however, their structural performance deteriorates significantly in soft or compressible subgrades due to their reliance on near-surface soil support. This often results in increased susceptibility to deformation, cracking, and differential settlement. In contrast, Spider Web Pavement systems

demonstrate enhanced structural resilience under such conditions, offering improved performance in environments characterized by low bearing capacity and high settlement potential.

**4.1 Structural Performance Comparison**

From a structural standpoint, the Spider Web Pavement system provides a more advanced load transfer mechanism by distributing traffic loads through a reinforced concrete slab supported by piles that extend into deeper, more competent soil layers. This configuration not only reduces stress concentrations at the subgrade level but also enhances overall load distribution efficiency and structural stability. Conversely, conventional pavement systems rely predominantly on the load-spreading capacity of layered materials and the subgrade's bearing capacity. As a result, their performance is highly sensitive to subgrade quality, making them more prone to excessive deformation and long-term structural deterioration when constructed on weak soils.

Table 1 presents a comparative evaluation of the structural performance between conventional pavement systems and Spider Web Pavement (slab-on-pile system), highlighting fundamental differences in load-bearing behavior, design requirements, and response to subgrade conditions.

**Table 1.** Comparative evaluation of the structural performance between conventional pavement systems and Spider Web Pavement

Parameter	Conventional Pavement	Spider Web Pavement
Minimum subgrade bearing capacity	Medium–High	Low
Pavement thickness (cm)	40–60	20–30 (concrete slab)
Differential settlement	High (on soft soils)	Very low
Load distribution mechanism	Layered system	Slab + piles

From the perspective of subgrade bearing capacity, conventional pavements require medium- to high-strength subgrade to function effectively. This is because their load distribution mechanism relies heavily on layered structural support, where stresses are gradually transferred from the surface layer to the underlying layers and ultimately to the subgrade. When the subgrade is weak or compressible, this dependency often leads to excessive deformation and structural distress. In contrast, the Spider Web Pavement system is designed to perform efficiently even on low-bearing-capacity soils, as it transfers loads through piles to deeper, more stable strata. This significantly reduces reliance on the immediate subgrade, making it particularly suitable for soft soil environments.

In terms of pavement thickness, conventional systems typically require thicker structures, ranging from 40 to 60 cm, to adequately distribute traffic loads and compensate for weaker subgrade conditions. The increased thickness is necessary to enhance stiffness and prevent excessive stress transmission. However, this approach results in higher material consumption and may not always guarantee long-term performance on problematic soils. Conversely, Spider Web Pavement uses a thinner concrete slab, typically 20-30 cm thick, since structural support is provided by piles. This combination of slab and deep foundation elements enables a more efficient structural design, reducing material use while maintaining, or even improving, performance.

Regarding differential settlement, which is a critical issue in pavement performance, conventional pavements are highly susceptible, especially when constructed on soft or heterogeneous soils. Variations in subgrade properties can lead to uneven settlement, causing surface cracking, rutting, and eventual structural failure. The Spider Web Pavement system demonstrates a significant advantage in this aspect, exhibiting very low differential settlement. The presence of piles ensures uniform load transfer to stable layers, minimizing deformation and maintaining structural integrity over time.

The most fundamental distinction lies in the mechanism for load distribution. Conventional pavements operate on a layered system, where each layer contributes to stress reduction through material stiffness and thickness. While effective under stable conditions, this mechanism becomes less reliable when subgrade support is inadequate. In contrast, the Spider Web Pavement employs a composite slab–pile system, where the reinforced concrete slab distributes loads laterally while the piles transfer them vertically to deeper soil layers. This dual mechanism enhances overall structural efficiency and reduces stress concentration within the pavement system.

The comparison shows that Spider Web Pavement provides superior structural performance, particularly under challenging geotechnical conditions. Its ability to function effectively on low-strength subgrades, minimize settlement, and optimize thickness makes it a robust alternative to conventional pavement systems. However, these advantages must be considered alongside other factors such as construction complexity and cost, which are discussed in subsequent sections.

**4.2. Technical Construction Comparison**

Table 2 presents a comparative analysis of the technical characteristics of conventional pavement systems and Spider Web Pavement (slab-on-pile systems), focusing on construction complexity, execution time, subgrade treatment requirements, and deformation resistance. These parameters are critical in

determining the feasibility and practicality of pavement implementation under varying field conditions.

**Table 2.** Comparative analysis of the technical characteristics of conventional pavement systems and Spider Web Pavement (slab-on-pile systems)

Technical Aspect	Conventional Pavement	Spider Web Pavement
Construction complexity	Low	High
Construction duration	Shorter	Relatively longer
Subgrade improvement need	High (soft soils)	Low
Resistance to deformation	Moderate	High

In terms of construction complexity, conventional pavement systems are generally considered low complexity due to well-established construction procedures, widespread availability of equipment, and familiarity among contractors. The processes involved, such as subgrade preparation, layer compaction, and asphalt or concrete placement, are standardized and can be executed with conventional machinery. In contrast, Spider Web Pavement systems exhibit high construction complexity, as they require specialized design considerations, precise pile installation, and integration between deep foundation elements and the surface slab. This complexity necessitates skilled labor, advanced equipment, and stricter quality control measures, which may limit their applicability in regions with constrained technical capacity.

Regarding construction duration, conventional pavements typically have shorter construction periods, primarily because of simpler construction stages and the absence of deep foundation work. This makes them suitable for projects with tight timelines or that require rapid infrastructure deployment. On the other hand, Spider Web Pavement systems involve additional processes, such as pile driving or drilling, reinforcement installation, and slab casting, resulting in a relatively longer construction duration. The extended timeline must be carefully considered in project planning, especially for large-scale infrastructure developments.

A key differentiating factor lies in the need for subgrade improvement. Conventional pavements often require significant subgrade treatment, particularly when constructed on soft or weak soils. Methods such as soil stabilization, compaction, or replacement are commonly employed to enhance bearing capacity and prevent premature failure. These additional treatments increase both time and cost. Conversely, the Spider Web Pavement system demonstrates a low dependency on subgrade improvement, as its structural design allows loads to be transferred to deeper, more stable soil layers through pile support. This reduces the need for extensive ground modification, making the system particularly

advantageous in geotechnically challenging environments.

In terms of resistance to deformation, conventional pavements generally exhibit moderate performance, as their structural integrity is influenced by material properties and subgrade conditions. Under heavy traffic loads or weak soil conditions, they are more susceptible to rutting, cracking, and long-term deformation. In contrast, Spider Web Pavement systems offer high resistance to deformation, owing to their integrated slab-pile configuration, which enhances stiffness and minimizes stress concentration. This results in improved durability and reduced maintenance requirements over time.

The technical comparison highlights a trade-off between simplicity and performance. Conventional pavements offer advantages in terms of ease of construction and shorter project timelines, making them suitable for standard conditions and limited budgets. However, Spider Web Pavement systems, despite their higher complexity and longer construction duration, provide superior technical performance, particularly in challenging subgrade conditions where conventional approaches may be insufficient.

#### 4.3. Cost and Service Life Comparison

Table 3 presents a comparative assessment of the economic performance of conventional pavement systems and Spider Web Pavement (slab-on-pile systems), focusing on initial construction cost, maintenance expenditure over a 10-year period, and overall design service life. These parameters are critical in evaluating not only short-term affordability but also long-term cost efficiency within a life-cycle perspective.

**Table 3.** Comparative assessment of the economic performance of conventional pavement systems and Spider Web Pavement (slab-on-pile systems)

Cost Component	Conventional Pavement (USD/m <sup>2</sup> *)	Spider Web Pavement (USD/m <sup>2</sup> *)
Initial construction cost	30–40	50–60
Maintenance cost (10 years)	High	Low
Design service life (years)	10–15	20–30

Note: \* Cost values are converted from local currency and presented as approximate ranges based on literature data.

Regarding initial construction costs, conventional pavements are generally more economical, with estimated costs ranging from USD 30 to 40 per square meter. This cost advantage is primarily attributed to simpler construction processes, the use of widely available materials, and the absence of specialized structural components such as piles. As a result,

conventional pavement systems are often preferred for projects with limited budgets or where immediate cost minimization is a priority. In contrast, Spider Web Pavement systems exhibit higher initial costs, typically ranging from USD 50–60 per square meter. The increased cost is mainly due to the inclusion of pile foundations and reinforced concrete slabs, as well as the need for specialized construction techniques and equipment. This represents an approximate 30–40% increase in upfront investment compared to conventional systems.

However, when considering maintenance costs over a 10-year period, the economic perspective shifts significantly. Conventional pavements are associated with high maintenance costs, particularly when constructed on weak or unstable subgrades. Frequent repairs are often required to address issues such as cracking, rutting, and settlement, which not only increase direct maintenance expenses but also incur indirect costs, such as traffic disruption and reduced serviceability. On the other hand, Spider Web Pavement systems require minimal maintenance, owing to their superior structural performance and resistance to deformation. The slab-on-pile system's ability to minimize subgrade stress reduces the risk of structural damage, thereby reducing the need for frequent interventions.

A key advantage of the Spider Web Pavement system is reflected in its design service life, which ranges from 20 to 30 years, significantly longer than the 10 to 15 years typically associated with conventional pavements. The extended service life is a direct consequence of improved load distribution, reduced differential settlement, and enhanced structural stability. In contrast, the shorter lifespan of conventional pavements often necessitates earlier rehabilitation or reconstruction, further increasing long-term costs.

When these factors are evaluated collectively, it becomes evident that although Spider Web Pavement systems require a higher initial investment, they offer superior life-cycle cost efficiency. The combination of reduced maintenance costs and extended service life offsets the higher upfront expenditure, making them a more sustainable and economically viable solution in the long term, particularly in areas with challenging subgrade conditions. Conversely, conventional pavements may remain advantageous in scenarios where budget constraints are critical and subgrade conditions are stable, minimizing the need for extensive maintenance.

The comparison highlights the importance of adopting a life-cycle cost analysis (LCCA) approach rather than relying solely on initial construction costs. Such an approach enables more informed decision-making by accounting for long-term performance, durability, and economic sustainability of pavement systems.

## 5. Discussion

The comparative results presented provide a comprehensive understanding of the structural, technical, and economic performance differences between conventional pavement systems and Spider Web Pavement (slab-on-pile systems). These findings highlight important trade-offs and reinforce the need for a holistic evaluation framework that integrates geotechnical conditions, structural behavior, and long-term sustainability considerations.

From a structural perspective, the results clearly indicate that Spider Web Pavement systems outperform conventional pavements in weak subgrade conditions. The slab-on-pile configuration enables efficient load transfer to deeper, more competent soil layers, thereby reducing stress concentrations and minimizing differential settlement. This finding is consistent with prior studies that emphasize that conventional pavements are highly dependent on subgrade strength and more vulnerable to deformation when constructed on soft soils (Rosyidi, 2021). In contrast, alternative structural systems such as nailed slabs and pile-supported pavements have demonstrated improved load distribution and reduced surface deflection, supporting their suitability for geotechnically challenging environments (Fitriyani et al., 2023).

The reduced pavement thickness observed in Spider Web systems further reflects their structural efficiency. While conventional pavements require thicker layered structures (40–60 cm) to compensate for weaker subgrades, the Spider Web system achieves comparable or superior performance with a thinner slab (20–30 cm) due to the contribution of deep foundation elements. This aligns with the broader shift in pavement engineering toward integrated structural–geotechnical solutions, rather than reliance solely on material thickness or subgrade improvement.

From a technical standpoint, the results reveal a clear trade-off between construction simplicity and structural performance. Conventional pavements remain advantageous due to their lower construction complexity and shorter implementation time, making them suitable for projects with limited technical capacity or urgent timelines. However, these advantages are offset by the need for extensive subgrade improvement in soft soil conditions, which can increase both cost and construction duration. In contrast, Spider Web Pavement systems require more sophisticated construction techniques, including pile installation and precise structural integration, resulting in greater complexity and longer execution time. Despite these challenges, their reduced dependence on subgrade treatment presents a significant advantage in problematic soils.

This finding is consistent with previous research indicating that innovative pavement systems often involve higher technical requirements but deliver superior performance and durability (Guo et al., 2025).

Moreover, advancements in construction technologies and equipment are expected to gradually reduce these technical barriers, facilitating wider adoption of such systems in the future.

The economic analysis further reinforces the importance of adopting a life-cycle perspective in pavement design. Although conventional pavements offer lower initial construction costs (USD 30–40/m<sup>2</sup>), their higher maintenance requirements and shorter service life (10–15 years) result in increased long-term expenditures. Conversely, Spider Web Pavement systems require a higher upfront investment (USD 50–60/m<sup>2</sup>), but their lower maintenance costs and extended service life (20–30 years) contribute to superior life-cycle cost efficiency. This finding aligns with studies emphasizing that sustainable pavement solutions should be evaluated based on total life-cycle performance rather than initial cost alone (Knott et al., 2019; Styer et al., 2024).

In addition, the reduced maintenance frequency associated with Spider Web systems has broader socio-economic benefits, including minimized traffic disruption, lower user costs, and improved service reliability. These indirect benefits are often overlooked in traditional cost comparisons but are increasingly recognized as critical components of sustainable infrastructure planning.

The discussion also highlights the role of sustainability in pavement engineering, extending beyond material innovation to include structural design optimization. While numerous studies have focused on sustainable materials such as recycled aggregates, warm-mix asphalt, and industrial by-products (Badran et al., 2023; Wu et al., 2025), the present findings demonstrate that structural innovations like Spider Web Pavement can further enhance sustainability by improving durability and reducing maintenance-related resource consumption. This supports the argument that achieving sustainable road infrastructure requires a combined approach integrating both material and structural advancements (Barbhuiya et al., 2025; Hasheminezhad et al., 2024).

Despite these advantages, the implementation of Spider Web Pavement systems is not without limitations. The higher initial cost and construction complexity may restrict their applicability in regions with budget constraints or limited technical expertise. Furthermore, uncertainties related to long-term performance under varying environmental and loading conditions warrant further empirical investigation. As noted in previous studies, the scalability and standardization of innovative pavement systems remain key challenges for widespread adoption (Guo et al., 2025; Naik et al., 2024).

The findings suggest that no single pavement system is universally optimal; rather, the selection should be based on a context-specific evaluation of subgrade conditions, traffic loading, project budget, and long-term

sustainability objectives. Conventional pavements remain suitable for stable soil conditions and cost-sensitive projects, whereas Spider Web Pavement systems offer a more robust and sustainable solution for weak subgrades and high-performance requirements.

This study contributes to the existing body of knowledge by providing an integrated comparison of conventional and Spider Web Pavement systems across structural, technical, and economic dimensions. The results underscore the importance of adopting a life-cycle and performance-based approach in pavement design, supporting more informed and sustainable decision-making in road infrastructure development.

## 6. Conclusions

This study provides a comprehensive comparative evaluation of conventional pavement systems and Spider Web Pavement (slab-on-pile systems) from structural, technical, and economic perspectives, with a particular focus on their applicability in varying subgrade conditions. The findings demonstrate that each pavement system possesses distinct advantages and limitations, reinforcing the importance of context-specific selection in road infrastructure development.

From a structural standpoint, Spider Web Pavement systems exhibit superior performance, particularly in weak or soft subgrade conditions. The integration of pile support enables efficient load transfer to deeper, more competent soil layers, thereby reducing stress concentrations, minimizing differential settlement, and enhancing overall structural stability. In contrast, conventional pavements rely heavily on subgrade strength and layer thickness, making them more susceptible to deformation and performance deterioration under unfavorable soil conditions.

In terms of technical characteristics, conventional pavements offer advantages in construction simplicity, shorter execution time, and lower technical requirements, making them suitable for projects with limited resources or stable geotechnical conditions. However, their dependence on subgrade improvement in weak soils can offset these benefits. Conversely, Spider Web Pavement systems require more complex construction processes and specialized equipment, resulting in longer implementation time, but provide higher resistance to deformation and reduced reliance on subgrade treatment.

From an economic perspective, conventional pavements present lower initial construction costs, which may be advantageous for short-term budget considerations. Nevertheless, their higher maintenance requirements and shorter service life reduce their long-term cost efficiency. In contrast, Spider Web Pavement systems, despite higher initial investment, demonstrate superior life-cycle performance through reduced maintenance needs and extended service life. This highlights the importance of adopting a life-cycle cost

approach in pavement selection rather than relying solely on initial cost comparisons.

The results indicate that Spider Web Pavement systems are a more sustainable and resilient solution for infrastructure development in areas with weak subgrade conditions, while conventional pavements remain appropriate for stable soils and cost-constrained projects. The study underscores that optimal pavement selection should be based on a balanced consideration of structural performance, technical feasibility, and long-term economic efficiency.

### 6.1. Implications and Future Research

This study contributes to advancing sustainable pavement engineering by emphasizing the role of structural innovation alongside material sustainability. However, further research is recommended to validate these findings through field experiments, long-term performance monitoring, and advanced modeling approaches. Additionally, future studies should explore integrating sustainable materials into Spider Web Pavement systems to further enhance environmental and economic benefits. In conclusion, adopting a performance-based and life-cycle-oriented approach is essential for achieving durable, cost-effective, and sustainable road infrastructure, particularly in geotechnically challenging environments.

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**Data Availability Statement:** The data used in this study are derived from publicly available sources, including peer-reviewed journal articles, technical reports, and published literature. All relevant data supporting the findings of this study are included within the article.

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