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Review of Asphalt Pavement Adaptation to Climate Change: Enhancing Resilience and Sustainability

A. Ab Latif [1],*, M. F. Muda[1], M. R. Zainudin[1], H. Dao[2]

[1]Faculty of Civil Engineering, Universiti Teknologi MARA (UiTM), Pahang Branch, Jengka Campus, Bandar Pusat Jengka, 26400 Jengka, Pahang, Malaysia
[2]Department of Computer Engineering, Faculty of Engineering, Princess of Naradhiwas University, Narathiwat 96000, Thailand

ABSTRACT - Climate change significantly accelerates the degradation of asphalt pavements due to elevated temperatures, heavy rainfall, flooding, and severe weather phenomena. These environmental stressors reduce pavement longevity, increase maintenance expenses, and pose safety risks. This study examined recent research on the effects of climate change on asphalt pavement performance and assessed adaptation strategies aimed at enhancing resilience and sustainability. The research consolidated discoveries concerning temperature-induced rutting, moisture-related fatigue cracking, and material deterioration resulting from freeze-thaw cycles. Essential adaptation strategies were categorised into three main types: material advancements, structural modifications, and maintenance technologies. Material developments emphasised high-performance binders, nanomaterial additions, and recycled components to enhance heat and moisture resistance. Structural changes improved drainage and energy efficiency, including the implementation of permeable pavements and thermoelectric systems. Maintenance strategies, such as optimisation-based scheduling, enhanced binder treatments, and predictive monitoring via the Internet of Things (IoT), provided proactive solutions to prolong pavement longevity. This study highlighted that effective adaptation relies on incorporating climatic data into design models and life-cycle cost evaluations. Despite the cost and technical capacity challenges, adopting climate-resilient technology is essential for sustainable road infrastructure. This research offered pragmatic recommendations to inform future engineering practices and policy decisions in climate-adaptive pavement design.

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1. INTRODUCTION

Climate change is a significant environmental challenge to the world today. The scientific consensus suggests that the global climate is warming, with human activities, particularly manufacturing and energy use, being the primary contributors to this issue.[1], [2]. Climate change poses significant challenges to infrastructure systems worldwide, particularly asphalt pavements, which form the backbone of transportation networks. Increasing global temperatures, severe weather occurrences, and variable precipitation patterns lead to faster pavement deterioration, resulting in higher maintenance expenses and reduced safety[3], [4]. The flexible pavement design methodologies also require incorporating climate factors, such as temperature and precipitation, into the modelling of pavement degradation [5]. This review investigated the impacts of climate change on asphalt pavements and explored adaptation strategies to enhance their resilience and sustainability. The discussion integrated insights from recent research, industry practices, and case studies to provide a comprehensive understanding of this critical issue. In addition, the review evaluated a wide range of adaptation strategies proposed to mitigate these effects, focusing on material improvements, design modifications, and maintenance practices. The techniques discussed in this review were derived from studies conducted in diverse climatic regions, including temperate, tropical, and freeze-thaw zones, highlighting the need for tailored approaches to different environmental conditions. This review was inspired by the growing awareness that existing asphalt pavement design and maintenance methods may not adequately address the effects of climate change. Key questions addressed in this review included: How do climate change stressors affect the performance and longevity of asphalt pavements? What adaptation measures have been successfully implemented across various regions, and how do they differ depending on local climate conditions? This review aimed to provide valuable insights into the most effective and practical adaptation strategies for asphalt pavements facing climate-induced stresses by addressing these questions.

2. Overview of Climate Impacts on Asphalt Pavements

2.1 Effects of Rising Temperatures

As the global climate continues to change, the effects of rising temperatures have become increasingly evident across various sectors, including the transportation infrastructure. The impact of elevated temperatures on asphalt pavement is a significant concern, as this material is commonly used in constructing roads, highways, and other paved surfaces. Increasing temperatures worsen thermal stress in asphalt pavements, resulting in rutting, cracking, and a shorter service

***CORRESPONDING AUTHOR | A. A. Latif** | ✉ amminudin738@uitm.edu.my

life. Elevated ambient temperatures decrease the rigidity of asphalt binders, diminishing load-bearing capability and heightening vulnerability to deformation.

Rising temperatures due to climate change significantly affect the performance and lifespan of asphalt pavement. The key impacts include increased deformation, structural stress, and changes in temperature distribution throughout the pavement layers. For instance, a rise in temperature due to climate change in China caused an increase in permanent deformation or rutting by 18.63% and 36.71%, presenting notable challenges to the design and structure of asphalt pavements[6]. The other study found that rising temperatures alter seasonal patterns and increase overall heat exposure, accelerating pavement materials' ageing and cracking. This shift reduced pavement life unless thickness was increased from 7% to 32% to protect the base and subgrade [7]. Previous studies found that asphalt surface layers showed the highest temperature during the daytime and moved to the base layer during the night, which led to cracking and surface degradation, especially in extreme climates [8]. In addition, the region with high temperatures and heavy rainfall also experiences an increase in rutting and cracking [9]. Thus, special asphalt mixes and designs must maintain stability in such environments. The overview of the previous research findings on the effect of rising temperature on the performance of asphalt pavement is shown in **Error! Reference source not found.**.

Table 1: Overview of Research findings related to the effect of rising temperature on asphalt pavement.

No.	References	Objectives	Results	Future Research
1	[10]	Review climate resilience strategies for pavements	Integration of adaptation strategies into pavement planning.	Develop practical adaptation frameworks and integrate them into policy.
2	[11]	Developing climate change adaptation for asphalt pavements in Canada.	Coastal areas require more intense adaptation measures.	Refinement of adaptation models and additional regional climate studies.
3	[12]	Assess the impact of climate change on asphalt pavements in China.	Temperature fluctuations significantly affect pavement performance.	Advanced predictive models for temperature-induced pavement degradation.
4	[13]	Analyse flexible pavement response to climate change	Flexible pavements need climate-responsive management.	Comprehensive mitigation-adaptation framework for pavement design.
5	[14]	Evaluate the environmental impacts of pavement adaptation measures.	Adaptation measures increase emissions, requiring mitigation.	Development of sustainable adaptation strategies minimising emissions.
6	[15]	Conduct a life cycle assessment of adaptation strategies.	Upgraded binders improve performance but also incur additional costs.	Economic feasibility analysis for implementing adaptation at a large scale.
7	[16]	Develop an adaptation framework for climate-resilient pavements.	Stepwise adaptation reduces financial risks in pavement planning.	Integration of climate resilience into pavement regulatory standards.
8	[17]	Investigate climate-responsive maintenance strategies for pavements.	Optimised maintenance extends pavement lifespan at lower costs.	Long-term analysis of maintenance effectiveness across climatic zones.
9	[18]	Apply fuzzy logic to predict pavement deterioration under climate change.	Fuzzy logic models improve climate impact predictions.	Enhancing machine learning models for improved pavement degradation prediction.
10	[19]	Study maintenance regimes on pavement design life.	Policy integration is essential for sustainable pavement maintenance.	Developing climate-responsive transport policies for long-term sustainability.
11	[20]	Assess climate change effects on asphalt binder selection.	Binder grade selection must consider future temperature shifts.	Creating a database for climate-based asphalt binder selection guidelines.
12	[21]	Analyse pavement watering as a heat mitigation technique.	Pavement watering provides temporary but not long-term cooling.	Optimising pavement-watering methods for prolonged heat reduction.
13	[22]	Evaluate frost adaptation measures for flexible pavements.	Freeze-thaw cycles require region-specific adaptation approaches.	Regional studies on freeze-thaw adaptation strategies for pavements.
14	[23]	Develop machine-learning-based maintenance policies for pavements.	AI-enhanced maintenance models enhance cost efficiency.	Advancing AI-based maintenance models for real-time adaptation strategies.
15	[24]	Assess the cost implications of freeze-thaw adaptation strategies.	Porous asphalt adaptation should focus on cost-effectiveness.	Developing cost-efficient adaptation strategies for porous asphalt.

2.2 Influence of Precipitation and Flooding

Precipitation and flooding significantly affect asphalt pavements' structural integrity and functional performance. The increased frequency and intensity of rainfall, as well as the rising occurrences of extreme flooding due to climate change, accelerate pavement deterioration and reduce service life. Previous research found that higher precipitation and flooding caused potholes, lower structural integrity, and frequent repair requirements[14], [25]. Prolonged and intense precipitation leads to moisture infiltration into pavement layers, causing the weakening of the subgrade and base layers. Increased water content reduces the stiffness of unbound materials, lowering the pavement's load-bearing capacity. For example, saturated subgrades lost strength and developed a phenomenon called "pumping," in which particles moved to the surface and eroded the pavement's foundation. Consequently, this increased rutting and fatigue cracking in the asphalt surface [11]. Excess moisture can separate the asphalt binder from the aggregate, a process known as stripping. This stripping weakens the bond between the binder and the aggregate, reducing the strength of the asphalt mixture. Stripped pavements are more prone to cracking, potholes, and permanent deformation, leading to increased maintenance costs and reduced lifespan [15]. Furthermore, saturated pavement layers exhibited lower resistance to traffic-induced stresses, resulting in accelerated rutting. Moisture reduced the interparticle friction within the base layer, causing deformation under heavy loads. This process was exacerbated in regions with high rainfall, resulting in permanent deformation in the wheel paths [12]. When asphalt is continuously exposed to water during flooding, the binder softens, which decreases the stiffness of the asphalt mix. This decreased stiffness makes the pavement more prone to rutting, fatigue cracking, and degradation. In extreme cases, prolonged waterlogging results in the development of permanent moisture-induced damage that cannot be reversed [3]. Flooding dramatically accelerates surface erosion, significantly diminishing the pavement's skid resistance and texture. This degradation not only compromises safety but also leads to increased maintenance costs and the need for premature repairs. The loss of surface texture compromises vehicle traction, increasing the likelihood of accidents and reducing the pavement's functional performance [21]. For instance, pavement sections exposed to frequent flooding require increased maintenance to restore structural and functional integrity. The costs associated with post-flood rehabilitation included the base layer, sealing cracks, and overlaying damaged surfaces. These costs burdened transportation agencies financially and increased life-cycle costs [16].

Long-term exposure to water reduces the load-bearing capacity of pavements, especially in flexible pavement systems. Excess water in the pavement system increases pore pressure, decreasing the effective stress and causing a loss of shear strength in the underlying layers. Flood-induced damage to pavements results in surface irregularities, depressions, and potholes, which increase the risk of traffic disruptions and safety hazards. Due to increased fuel consumption and tyre wear, poor pavement conditions also affect ride quality and increase vehicle operating costs. Future research and mitigation efforts must prioritise enhancing the resilience of asphalt pavements to heavy precipitation and flooding, which are increasingly frequent due to climate change. One key research direction was the development of hydrophobic and moisture-resistant materials, particularly binders and modified aggregates that resist stripping and water-induced damage. This study included exploring nano-modified binders, polymer additives, and rejuvenators that improve moisture resistance and maintain binder-aggregate adhesion under saturated conditions [15] . Advanced drainage systems should also be studied and implemented. Research should investigate sub-surface drainage layers, permeable base courses, and innovative drainage systems that can adapt to varying moisture loads and mitigate water accumulation within pavement layers. In tandem, predictive hydrological-pavement models that combine rainfall data with pavement performance metrics can enhance maintenance and planning efforts [4]. Pavement structural design methodologies need refinement to incorporate climate-based risk modelling. Future work should examine resilient base and subbase materials with high water tolerance, such as geosynthetic-reinforced layers or foamed bitumen-stabilised bases, which can maintain their strength in saturated conditions [12]. Maintenance strategies should also shift toward adaptive management systems. Research into machine learning models to detect early-stage moisture damage, such as pumping stripping, can support real-time intervention and reduce long-term costs [23]. Depending on the severity, post-flooding rehabilitation must be optimised using cost-benefit analyses to prioritise interventions like crack sealing, overlaying, or full-depth reclamation [16]. Finally, policy and design standards must advance to incorporate flooding resilience as a fundamental criterion. Incorporating these findings into national specifications will ensure the scalability of these innovations, reduce life-cycle costs, and maintain safety and functionality under extreme weather conditions [21].

2.3 Extreme Weather Events

Hurricanes, storms, and heat waves impose abrupt and severe pavement stresses. For instance, excessive rainfall during storms accelerated wear, while heatwaves caused rapid binder oxidation, leading to premature ageing [26].

Extreme weather can cause significant damage to asphalt roads in various ways. Flooding is one of the most harmful events. When water covers the road for a long time, it weakens the layers under the asphalt. This flooding can cause the road to sink, crack, or break more easily. Roads built on clay or sand soil are more at risk. After significant floods, such as the one in Louisiana in 2016, many roads deteriorated rapidly due to water damage and the weight of heavy trucks during cleaning [27], [28].

Extremely high temperatures, such as heat waves, adversely affect asphalt. Elevated temperatures make the asphalt pliable. Moreover, the soft asphalt can be depressed by vehicles, resulting in ruts and depressions. Previous studies demonstrated that the heat induces the formation of cracks as the road heats up during the day and cools at night, resulting

in expansion and contraction [26]. This oscillatory motion deteriorates the road over time, particularly in areas exposed to significant sunlight.
In colder climates, snowstorms and freeze-thaw cycles cause additional damage. Water infiltrates pavement cracks and pores, freezes, and expands, leading to cracking, potholes and delamination. Icy conditions also reduce pavement friction, impacting traffic safety. Porous asphalt pavements are particularly vulnerable, as they freeze more readily and become slippery. Intense rainfall events further contributed to pavement degradation by increasing moisture damage and reducing structural strength through waterlogging [29]. Extreme weather events diminish the longevity and safety of asphalt pavements, underscoring the critical necessity for climate-resilient materials, enhanced drainage systems, and adaptive maintenance practices.

2.4 Pavement Performance Indicators

Climate change is increasingly recognised as a critical factor influencing the performance and longevity of road pavements. Environmental conditions have a significant impact on pavement design life and maintenance requirements. Rising temperatures, altered precipitation patterns, and more frequent extreme weather events have accelerated pavement degradation, leading to premature failures such as rutting, cracking, and roughness. These changes necessitate re-evaluating traditional pavement design and maintenance strategies to ensure road infrastructure resilience. Neglecting the impact of climate change on pavement management can result in higher life-cycle costs and reduced serviceability. Consequently, **Error! Reference source not found.** below illustrates the overview of the performance degradation of pavements due to climate change. The data were acquired from the prior study conducted by the researchers.

Table 2: Performance Degradation Metrics

Performance Indicator	Impact Range	Temporal Scale	References
Rutting	9% to 40% increase	Over the next 20 years	[6], [30], [31]
Fatigue Cracking	2% to 9% increase	Over the next 20 years	[32]
Permanent Deformation	18.63% to 36.71% increase	Under 1.5°C to 2.0°C global temperature anomaly	[6]
Low-Temperature Cracking	20.99% decrease	From 1970 to 1997	[6]
International Roughness Index (IRI)	Up to a 22.5% increase in deterioration rate	By the end of the century (2080-2099)	
Pavement Service Life	7 to 14 years reduction	No mention found	[13]
Thermal Cracking	Up to a 35% increase in severity	By 2050s	
Compressive Strength	Negative effect at normal temperature, minimal effect under extreme conditions	No mention found	

3. Material Innovations for Climate Adaptation

Modifying asphalt binders represents a critical area of research and development, driven by the imperative to enhance pavement performance. Researchers are continually searching for modifiers that enhance the rheological properties of asphalt binders and improve their adhesive strength. These elements create durable and resilient road surfaces [33]. Researchers have been actively exploring various innovative materials to enhance the performance of asphalt pavements in response to climate change, such as high-performance asphalt binders, recycled materials, and additives.

3.1 High-Performance Asphalt Binders

Due to climate change, many countries, including Malaysia, are experiencing higher temperatures. This condition causes asphalt pavements to become softer and more easily damaged. One way to solve this problem is to use high-performance asphalt binders that resist high temperatures. These special binders help reduce pavement damage, such as rutting, which means less maintenance is needed [34]. As a result, it helps reduce road repair costs and lowers carbon emissions from road works.

Temperature-resistant binders are especially effective in hot areas. For example, binders modified with polymer or other additives showed better strength and flexibility when exposed to high temperatures [35]. These binders performed better during long periods of heat and heavy traffic, which helped increase the pavement's lifespan. Therefore, using this type of binder was both cost-effective and environmentally friendly [36].

Another critical method was upgrading the binder grade using the Superpave system. Engineers used future temperature data to choose stronger binder grades that withstood more heat. For example, a pavement that previously required a PG 64-22 binder may need a PG 76-10 binder to accommodate the new climate conditions [37]. Choosing the correct grade helped the pavement stay strong and safe for longer.

Many researchers focused on using high-performance asphalt binders to improve pavement strength and performance under changing climate and traffic conditions. These binders were modified using polymers, nanomaterials, waste-based geopolymers, recycled plastics, and bio-derived substances [38], [39]. Each type of modification helped the pavement perform better, especially under high temperatures and heavy traffic. Polymer-modified binders, especially those with high polymer content, resisted fatigue, rutting, and thermal cracking [40]. These polymers improved the flexibility and strength of the binder, which extended pavement life and reduced repair costs [41].

In addition, nanomaterials like titanium dioxide (TiO_2) and silicon dioxide (SiO_2) were added to the binder to improve its strength under heat. These materials helped the pavement resist permanent deformation [42]. Geopolymer materials made from waste like fly ash and metakaolin were also used to modify asphalt binders. These waste-based geopolymers improved high-temperature performance and reduced environmental impact [43]. This method supported sustainable development goals in road construction.

Recycled plastics such as Recycled High-Density Polyethylene (RHDPE) and Recycled Polypropylene (RPP) improved rutting resistance and increased binder elasticity at high temperatures [38]. Meanwhile, reclaimed asphalt pavement (RAP) mixed with bio-binders maintained performance across various climates while promoting recycling. **Error! Reference source not found.** shows the Summary of the innovation in producing High-performance Asphalt Binders.

Table 3: Summary of the innovation in the production of High-performance Asphalt Binders

INNOVATION	BENEFITS	REFERENCES
Temperature Resistance Binders	Reduced maintenance, CO2 emissions, extended service life	[34]
Superpave Asphalt Binder Grades	Mitigated deterioration and climate resilience	[35], [36], [37]
Bio-Derived Binders	Sustainability, thermal cracking resistance	[39]
WEO Modified Binders	Enhanced flexibility, workability, and stability	[44]
Recycled Plastics	Improved rutting resistance, elasticity	[38], [45]
RAP with Bio-Derived Binders	Fatigue, deformation, and cracking resistance	[39]
Nano Materials	High-temperature stability, durability	[40], [41]
Geopolymer-Modified Binders	High-temperature performance, reduced emissions	[40], [42]

3.1 Structural Innovation of Asphalt Pavement

Climate change presents a growing challenge to asphalt pavements' long-term performance and durability. Rising temperatures, increased precipitation variability, and more frequent extreme weather events demand adaptive strategies to ensure infrastructure resilience. Structural innovations in pavement design offer promising solutions to mitigate these impacts while promoting sustainability. For example, concrete overlays effectively extended pavement life under increased thermal loading [13]. Meanwhile, geothermal pipe systems integrated within pavements provided a passive temperature regulation mechanism, limiting rutting and thermal cracking during extreme heat [46].

Increased asphalt layer thickness delayed surface distress, particularly under future warming scenarios [6]. Stabilised base layers, especially cementitious or recycled materials, enhanced load distribution and moisture resistance, critical under intensified rainfall and flooding conditions. Besides, permeable pavements managed stormwater runoff and diminished subgrade saturation, mitigating hydrological extremes associated with climate change.

Therefore, innovative energy-harvesting technologies, including thermoelectric systems integrated into asphalt, transformed waste heat into usable energy, thereby improving pavement thermal performance and advancing sustainable energy objectives. These structural modifications collectively demonstrated a transition to robust and multifunctional pavement systems. These advances were essential for climate-responsive infrastructure development, especially in susceptible areas with deteriorating road systems and constrained maintenance funds. Most strategies had significant initial costs, while others experienced a cost increase. **Error! Reference source not found.** shows the structural innovation of asphalt pavement and the cost implications.

Table 4: Structural Innovation of Asphalt Pavement and Cost Implications

Strategy Type	Effectiveness rating	Cost Implication	References
Concrete overlay	High	High initial cost	[13]
Geothermal pipes integration	Medium	High initial cost	[46]
Increases asphalt layer thickness	Medium to High	Moderate increase	[6]
Stabilised base layers	High	Moderate to high increase	[47]
Permeable pavement	Medium to high	High initial cost	[48]
Embedded heat exchange system	Medium	High initial cost	[32]
Thermoelectric system	Low to medium	High initial cost	[49]

4. Maintenance Strategies for Climate Resilience

Recent research found several effective maintenance strategies that enhance the climatic resilience of asphalt pavements. These strategies emphasised the integration of technology for predictive maintenance, the optimisation of maintenance schedules, and the use of advanced materials.

4.1 Optimisation of Maintenance Schedule

Optimising maintenance schedules is a key strategy in adapting asphalt pavements to the increasing variability of climate conditions. The accelerating effects of climate change, such as increased rainfall, higher mean temperatures, or heat waves, are often not considered in traditional maintenance planning, which frequently adheres to periodic or condition-based models. This optimisation entails setting performance thresholds tailored to climate-induced stresses. Early maintenance interventions for rutting or cracking due to elevated temperatures or moisture infiltration can mitigate additional structural damage and extend service life. Maintenance triggers were established dynamically, contingent upon the rate of distress progression under anticipated climate scenarios. The threshold-based approach facilitated flexibility and responsiveness, ensuring that appropriate interventions were implemented at the most cost-effective moments. Furthermore, optimisation strategies should incorporate geographically specific climate data into pavement management systems. Distinct climate zones pose diverse challenges; desert regions necessitate increased attention to thermal cracking, whereas coastal or tropical areas may encounter issues related to water damage, including subgrade weakening or stripping. Optimisation, while effective, encounters practical challenges. Accurate climate projections, dependable pavement deterioration models, and high-quality monitoring data are crucial for success. Additionally, the implementation may be limited by institutional capacity and funding availability. Strategic investment in optimising maintenance schedules represented a low-risk, high-benefit method for improving the resilience and cost-efficiency of road networks facing climate stress.

4.2 Advanced Materials and Techniques

Using advanced materials and techniques in asphalt pavement maintenance presented a significant method for enhancing climate resilience. Conventional asphalt mixtures degraded performance when exposed to extreme temperatures, moisture fluctuations, increased traffic volumes and higher traffic loads. All of these issues were made worse by climate change. Modified binders and functional additives enhanced durability, flexibility, and pavement performance. Polymer-modified asphalts demonstrated enhanced resistance to rutting under elevated temperatures and cracking under reduced temperatures. These binders exhibited flexibility under dynamic loading, rendering them especially effective in areas with significant temperature variations. Moreover, recent advancements included the incorporation of nanomaterials, such as nano-silica and nano-clay, which enhanced the thermal conductivity, stiffness, and ageing resistance of the asphalt matrix. The modifications decreased the pavement's vulnerability to climate-related stress and extended its service life. Alongside material enhancement, healing technologies, including induction heating, microwave heating, and encapsulated rejuvenators, are receiving increased attention. These methods facilitated the in-situ repair of microcracks before their progression into significant structural failures. Over the last ten years, self-healing technology has progressed in asphalt pavement design. Self-healing technology provided an alternate approach to road maintenance, wherein damage was rectified by an internal (implanted) healing mechanism [50]. Although these techniques offer notable performance benefits, the cost continues to hinder widespread adoption. Modifying polymers and applying nanotechnology require advanced processing techniques and strict quality control protocols, while healing systems necessitate the integration of embedded components and specialised maintenance tools. Thus, in the context of life cycle performance, these innovations can yield long-term savings by decreasing the frequency and severity of repairs.

4.3 Predictive Maintenance Technologies

Predictive maintenance technologies represented a paradigm shift in pavement management, moving from reactive and periodic interventions to proactive and data-driven strategies. The acceleration of climate change has increased the frequency and severity of pavement distress, including rutting, fatigue cracking, and thermal damage, thereby heightening the urgency for intelligent systems to predict failures. Predictive maintenance employs sensors, real-time monitoring, and advanced analytics to anticipate pavement condition trends and initiate prompt interventions. It relies on implementing Internet of Things (IoT) technologies.
For instance, embedded or surface-mounted sensors continuously collected data on surface temperature, moisture levels, strain, and load responses. Data were transmitted to pavement management systems, where machine learning models analysed the information to identify distress patterns or anomalies. The integration of sensor feedback with historical performance data enhanced the accuracy of predicting maintenance needs regarding timing and location. Machine learning algorithms, including artificial neural networks (ANN), random forests, and support vector machines (SVM), were utilised to predict deterioration across different climate conditions. These models adjusted to local climate inputs and modified predictions in response to incoming data. Predictive analytics improved resource allocation by prioritising interventions according to actual pavement requirements instead of predetermined schedules. Implementation barriers included the significant initial costs associated with instrumentation, the need for robust data processing infrastructure, and the necessity for skilled personnel to manage and interpret the outputs.

Predictive maintenance served as an effective mechanism for climate adaptation. It reduced unforeseen failures, enhanced safety, and prolonged pavement durability through optimised resource utilisation. With the increasing affordability and accessibility of technologies, predictive strategies were set to play a fundamental role in resilient pavement maintenance planning.

4.3 Key Challenges Emerge During the Implementation of Maintenance Strategies

High initial costs, limited technical capacity, and the need for robust data infrastructure can hinder widespread implementation. Supportive policies, focused funding, and interdisciplinary collaboration are essential for addressing these barriers. Infrastructure agencies can improve the climate resilience of pavement networks by implementing a proactive, systems-oriented strategy that combines technological advancements with environmental adaptation. This transition will improve performance across different climatic conditions and support sustainability goals by reducing emissions, conserving resources, and enhancing service delivery throughout the asset life cycle. The maintenance strategies for asphalt pavement climate resilience are shown in Table 5.

Table 5: Maintenance Strategies for Asphalt Pavement Climate Resilience

Maintenance Strategies	Effectiveness	Cost Implication	References
Optimisation-based maintenance	High	Initial increase, long-term savings	[51]
Proactive rehabilitation scheduling	Medium to High	Moderate increase	[13]
Climate-informed inspection frequency	Medium	Low to moderate increase	[52]
Use of climate projections in maintenance planning	High	Low increase, potential long-term savings	[6]
Adaptive maintenance timing	Medium to High	Moderate increase	[51]
Integration of real-time monitoring	Medium	High initial cost, potential long-term savings	[53]
Life cycle cost analysis for maintenance decisions	High	Low increase, significant long-term benefits	[54]

5. CONCLUSIONS

Climate change poses significant challenges for asphalt pavement performance, leading to more frequent and severe structural issues through rutting, thermal cracking, moisture-induced degradation, and freeze-thaw damage. This review explored the multifaceted impacts of climate stressors on pavement systems and evaluated a broad set of adaptation strategies to enhance resilience and sustainability. Material innovations, including polymer-modified binders, nanomaterials, recycled plastics, and bio-binders, demonstrated strong potential in improving asphalt's mechanical and thermal properties under extreme climate conditions. Structural innovations such as concrete overlays, stabilised base layers, geothermal integration, and thermoelectric systems addressed localised environmental stressors while promoting energy efficiency and hydrological stability. Maintenance strategies that emphasised optimisation scheduling, advanced self-healing methods, and predictive analytics using IoT and artificial intelligence (AI) demonstrated the potential to reduce damage escalation and life-cycle costs. However, widespread implementation of these strategies is often limited by initial capital costs, technological complexity, and lack of institutional readiness. Therefore, future work must develop region-specific adaptation frameworks, improve predictive climate-pavement models, and enhance cost-effectiveness through scalable technologies. Incorporating climate adaptability into pavement design guidelines and asset management systems is essential. The active adjustment of asphalt pavement technologies is necessary for infrastructure that is prepared for the future. Using a collaborative approach that combines engineering innovation, data science, and policy support, the road construction sector can significantly enhance its ability to resist climate change while fostering environmental and economic sustainability.

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Conflict of Interest

The authors declare no conflicts of interest.

Authors' Contribution

Amminudin Ab Latif (Conceptualization; Idea formulation; Study Objectives; Scope of review; Writing draft article: Critical revision: Editing)

Mohd Fakri Muda (Literature search; Identify relevant studies; Writing draft article; Critical revision; Editing)

Mohd Razmi Zainuddin (Literature search; Identify relevant studies; Writing draft article; Critical revision; Editing)

Availability of Data and Materials

The data supporting this study's findings are available on request from the corresponding author

Ethics Statement

Not applicable

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