

CLIMATE CHANGE AND ITS EFFECTS ON ROAD PAVEMENT PERFORMANCE: A REVIEW OF CURRENT RESEARCH

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ABSTRACT

Climate change, marked by long-term shifts in temperature, precipitation, and other atmospheric conditions, significantly challenges pavement infrastructure. This review synthesises research on climate change effects on pavement performance, highlighting temperature fluctuations and altered precipitation patterns as key factors affecting pavement durability and functionality. Temperature extremes cause asphalt softening, rutting, and increased freeze-thaw cycles, which lead to cracking and structural damage. Precipitation changes, including heavy rainfall and droughts, weaken pavements and accelerate material deterioration. The review explores adaptation strategies, such as advanced materials (e.g., modified asphalt binders) and design adjustments (e.g., increased pavement thickness and enhanced drainage). It also highlights mitigation measures, such as using recycled materials and energy-efficient practices, that are essential for reducing the carbon footprint of infrastructure projects. Coordinated policy efforts, updated design codes, and investment in resilient materials are crucial for integrating climate considerations into infrastructure development. Future research should focus on innovative solutions and practical guidelines for engineers and policymakers to ensure road infrastructure resilience and sustainability under changing climatic conditions.

Keywords: *Climate change adaptation, road infrastructure resilience, pavement performance, temperature fluctuations, precipitation patterns*

INTRODUCTION

Climate change poses a significant challenge to transportation infrastructure, particularly pavements, which are vulnerable to its effects. Rising global temperatures and shifting precipitation patterns necessitate understanding these impacts, in order to design and maintain resilient road networks. Elevated temperatures can soften asphalt layers, leading to deformation and structural weakening, while increased precipitation exacerbates waterlogging and reduces the load-bearing capacity of pavements. Freeze-thaw cycles in colder regions further contribute to pavement cracking and degradation. These issues underscore the need for climate-resilient infrastructure planning and adaptation strategies [1]-[2]. Road infrastructure is

vital for socioeconomic development, facilitating trade, mobility, and overall economic activity. Pavement design and maintenance have traditionally relied on historical climate data, assuming stable climatic conditions. However, with evident climate variability, such assumptions are increasingly inadequate. Experts predict that climate change will significantly reshape how transportation infrastructure is planned, built, and maintained [3].

Climate change, driven by industrial emissions and deforestation, leads to long-term changes in temperature and precipitation. Reports show rising global temperatures and altered rainfall patterns over

the past century, challenging traditional pavement designs based on historical data [4]. High temperatures accelerate asphalt ageing, causing embrittlement and reducing service life. In colder climates, freeze-thaw cycles intensify, leading to severe cracking and pothole formation. Additionally, variations in precipitation impact subgrade strength and pavement durability, highlighting the need for design modifications and improved drainage systems [2],[5].

Adaptation strategies for pavements include using advanced materials like polymer-modified asphalts and enhancing drainage systems to counter moisture-related damage. Mitigation measures focus on reducing the carbon footprint of pavement construction, including recycled materials and green infrastructure elements like permeable pavements [3]. Maintaining resilient road networks is essential for transportation reliability, economic growth, and safety. Policymakers and engineers must incorporate climate resilience into pavement management through updated standards and coordinated efforts [6].

Several case studies highlight the regional impact of climate change on pavements and the effectiveness of adaptation strategies. For example, incorporating climate risk assessments into transport projects in the Solomon Islands has resulted in more resilient designs [7]. Similarly, European research emphasises tailoring adaptation measures to regional climatic hazards, while African studies highlight the economic strain of maintaining road networks under changing conditions [8]. Future research should enhance climate models, develop innovative materials, and assess the economic implications of adaptation strategies. Interdisciplinary collaboration is key to fostering comprehensive, sustainable solutions [9].

Challenges remain, including financial constraints, regulatory barriers, and uncertainties in climate projections. Addressing these requires updated design codes, standardising best practices, and knowledge sharing across regions. Pilot projects and real-world studies can validate new materials and designs, providing more effective solutions. Ultimately, integrating climate resilience into standard engineering practices is critical for the sustainability of road networks in the face of climate change [3]. This paper aims to provide a comprehensive review of the impact of climate change on pavement performance,

focusing on key climatic factors such as temperature and precipitation. Understanding these impacts is crucial for developing effective adaptation and mitigation strategies to ensure the resilience and sustainability of road infrastructure.

The remaining parts of the paper discuss the importance of road infrastructure in socioeconomic development and challenge traditional assumptions in pavement design and maintenance. It highlights the specific impacts of temperature and precipitation on pavement performance, examines other climatic stressors, and presents case studies and regional impacts. The paper outlines current adaptation and mitigation strategies, emphasising the need to integrate climate change considerations into infrastructure development processes. Finally, it summarises key takeaways and provides recommendations for future research and policy directions to address climate change challenges in pavement infrastructure.

METHODS

This review systematically examined the impacts of climate change on performance, as well as the associated adaptation and mitigation strategies. synthesising research studies, technical reports, and industry guidelines to identify knowledge gaps and inform future research.

In addition, the systematic review was designed to ensure transparency, replicability, and objectivity in synthesising the available evidence. Figure 1 shows the methodology flowchart, which illustrates the structured process of source identification, screening, and data extraction. By following a structured process of source identification, screening, and data extraction, the review minimised selection bias. It also ensured that only studies with methodological rigour and relevance were included. The findings were categorised into thematic areas such as temperature effects, precipitation effects, climatic stressors, and adaptation and mitigation measures. This approach allowed for a nuanced analysis that highlights both converging insights and areas of divergence across studies.

Step 1: Source Identification

Relevant sources were gathered using academic databases such as Google Scholar, Web of Science,

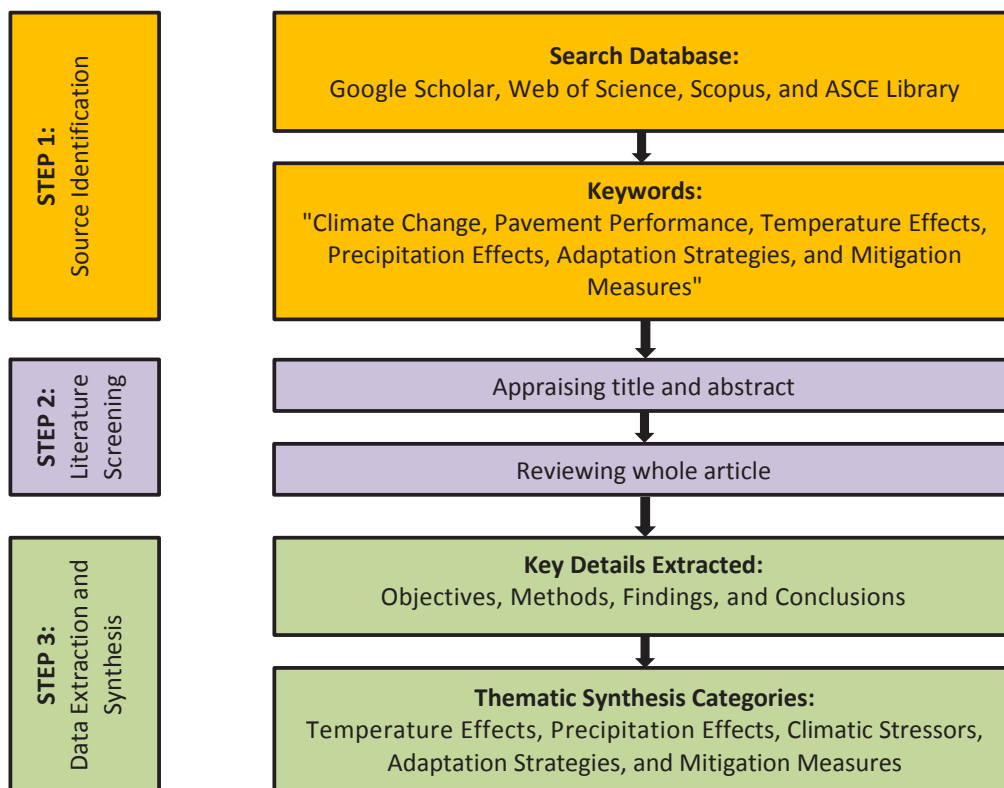


Figure 1 Methodology flowchart

Scopus, and the ASCE Library, employing keywords such as “climate change,” “pavement performance,” “temperature effects,” “precipitation effects,” “adaptation strategies,” and “mitigation measures.” Additional searches included reports from major organisations, such as the Intergovernmental Panel on Climate Change (IPCC), the United Nations Framework Convention on Climate Change (UNFCCC), the Federal Highway Administration (FHWA), the National Academies of Sciences, Engineering, and Medicine (NASEM), and the Transportation Research Board (TRB).

Step 2: Literature Screening

A multi-stage screening process was applied to filter the initial pool of sources. Titles and abstracts were first reviewed for relevance, followed by full-text evaluations to ensure methodological rigour and significance. Priority was given to studies offering empirical data, case studies, or innovative strategies.

Step 3: Data Extraction and Synthesis

Key details were extracted from selected studies, including objectives, methods, findings, and conclusions. Data were synthesised into thematic categories such as temperature effects, precipitation

effects, climatic stressors, adaptation strategies, and mitigation measures to identify patterns and gaps.

Data Analysis

Extracted information was summarised in a structured table to clearly present climate change impacts and proposed adaptation strategies. This summary facilitated thematic discussions and is presented in Table 1.

OVERVIEW OF CLIMATE CHANGE

Climate change involves long-term shifts in temperature, precipitation, and other atmospheric conditions, driven primarily by human activities such as fossil fuel combustion, deforestation, and industrial processes. These activities increase greenhouse gas (GHG) concentrations [24]. These gases, such as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), trap heat, causing global warming through the greenhouse effect. Historical insights, including 19th-century discoveries by John Tyndall and Svante Arrhenius and Charles Keeling’s 1950s CO₂ measurements, highlight human

Table 1 Impact of climate factors on pavement performance and adaptation strategies

Source	Factor Considered	Impact on Road Pavement	Adaptation Strategy Proposed
[10]	Temperature, rainfall, storm surges, sea level rise	Melting of bitumen, flooding, landslide, traffic disruption	Review design standards, introduce policy on climate change, increase maintenance frequency
[11]	Sea level rise	Erosion and subsidence of road bases, flooding, traffic congestion	Use of dikes, seawalls, beach nourishment, elevation of roads, pervious materials
[12]	Temperature, precipitation	Increase in fatigue cracking, increase in pavement design Rutting	Consider projected climate during pavement design
[13]	Temperature, moisture, storm surge, sea level rise	Rapid aging of asphalt, cracking, increased deterioration rate	Increase maintenance cost
[14]	Rainfall	Increased flooding, landslides, subsidence induced failure	Use green infrastructure, sustainable urban drainage systems
[15]	Temperature, sea level rise	Premature pavement failure	Apply hot mix asphalt overlay, increase base layer thickness
[16]	Temperature, precipitation, relative humidity	Increased rutting, increased roughness, increased cracking	Upgrade asphalt binder
[9]	Temperature	Increase in pavement rutting, increased thermal cracking	Consider projected climate during pavement design
[17]	Temperature, precipitation, solar radiation, wind	Degradation, pavement rutting, fatigue cracking, thermal aging	Temperature monitoring, use of expansion joints, improved drainage, waterproofing treatments, resistant bituminous mixes
[18]	Precipitation	Erosion, landslides	Use concrete culverts with bigger dimensions, dry water ponds, permeable asphalt
[19]	Temperature Variability, Precipitation Patterns, Freeze - Thaw Cycles, Sea Level Rise, Soil Saturation	Reduced Service Life, Increased Maintenance Costs, Performance Degradation	Scenario-Based Approach, Asset-Based Approach, Hybrid Approach Life Cycle Assessment (LCA)
[20]	Temperature, precipitation	Increase in rutting and fatigue cracking	Upgrade binder grade, increase thickness of asphalt concrete and base layer, use stabilised base layer
[21]	Temperature, precipitation, sea level rise	Travel speed reduction, accelerated pavement degradation	Use permeable, cool, and less temperature-sensitive pavements, use salt-resistant pavements
[22]	Temperature, precipitation	Increased fatigue cracking, increased rutting	Increase pavement layer thickness, use stiffer binders, more steel reinforcement, load allowances/restrictions, use of geotextiles
[23]	Temperature Precipitation Solar Radiation Wind Humidity Cloud cover Freeze-thaw cycles	Reduced service life: Shorter pavement lifespan due to accelerated deterioration Increased maintenance costs: Higher costs for repairs and rehabilitation Performance degradation: Decline in ride quality and structural integrity	Use high-quality asphalt binders with lower PG limits for better low temperature resistance. Enhance pavement drainage with proper mix designs. Protect asphalt from aging with antioxidant additives and fog seals. Incorporate climate change predictions into pavement design and maintenance. Implement resilience strategies for extreme weather events.



Figure 2 California wildfire [27]

contributions to this phenomenon. These are now substantiated by climate models and observational data [25]. Climate change disrupts ecosystems, alters species distributions, and threatens marine life through ocean acidification [26], while also contributing to extreme events such as wildfires (Figure 2).

It affects agriculture by altering crop yields and increasing pest prevalence, jeopardising food security [28]. Health impacts include heat stress, the spread of diseases, and worsened air quality, disproportionately affecting vulnerable populations [29]. This is exemplified by severe smog events in urban areas like Lahore (Figure 3). Climate-related shifts in freshwater availability also challenge drinking water supplies, agriculture, and hydropower [30].

Mitigation efforts focus on reducing GHG emissions through renewable energy, energy efficiency, reforestation, and sustainable agriculture, supported by

policies such as carbon pricing and emission trading [32]. Adaptation measures aim to enhance resilience through infrastructure improvements, early warning systems, water management, urban planning, and ecosystem-based approaches [33].

Global cooperation is vital, as emphasised by agreements such as the UNFCCC, Kyoto Protocol, and Paris Agreement, which aim to limit warming and foster international collaboration on mitigation and adaptation [34]. Continued research, technological innovation, and public engagement are critical for advancing climate solutions and building resilience [35].

Temperature Effects on Pavements

Climate change significantly affects pavement performance, particularly through temperature variations. Higher temperatures can lead to the softening of asphalt pavements, causing rutting



Figure 3 Street engulfed in smog in Lahore [31]



Figure 4 Photo demonstrating an example of asphalt layer rutting [38]

and deformation, which compromise the structural integrity and safety of roadways (Figure 4) [36]. As asphalt softens, it becomes more pliable, leading to permanent deformation under the pressure of traffic loads. This is especially problematic during prolonged heatwaves, where sustained high temperatures can exacerbate the severity of rutting [37].

Increased temperatures also accelerate the oxidation process of asphalt binders. Oxidation causes the asphalt to harden and become more brittle, increasing the likelihood of cracking (Figure 5). Over time, the binder loses its ability to effectively bind aggregates, leading to surface ravelling and the formation of cracks. These cracks can propagate quickly, especially under heavy traffic, significantly reducing pavement life and increasing maintenance costs [39].

Moreover, temperature fluctuations associated with freeze-thaw cycles pose another challenge. When water infiltrates cracks and voids in the pavement, it can freeze

and expand during cold weather, exerting pressure on the pavement structure [41]. As temperatures rise, the ice melts, leaving gaps that can lead to further water infiltration and subsequent freeze-thaw cycles. This repeated process can cause significant damage to both asphalt and concrete pavements, leading to potholes, spalling, and other forms of surface deterioration (Figure 6). The cumulative effect of these freeze-thaw cycles can severely compromise the structural integrity of pavements, necessitating frequent repairs and increasing maintenance costs [42].

Several indicators provide clear evidence of climate change. The Earth's average surface temperature has risen by approximately 1.1°C since the late 19th century, with most of this warming occurring in the past 35 years [44]. The oceans have absorbed much of the increased heat, with the top 700 m showing significant temperature increases. Polar ice sheets in Greenland and Antarctica are losing mass, contributing to rising sea levels, while glaciers are retreating globally,



Figure 5 Thermal cracking [40]



Figure 6 Pavement spalling [43]

impacting freshwater supplies and ecosystems [45]. Additionally, the extent and duration of snow cover in the Northern Hemisphere have decreased, reflecting changes in seasonal weather patterns [46]. Global sea levels have risen by about 20 cm in the past century, driven by melting ice and thermal expansion of seawater (Figure 7). There has also been an uptick in the frequency and intensity of extreme weather events, including hurricanes, heatwaves, droughts, and heavy precipitation [35].

Precipitation Effects on Pavements

Climate change has led to significant shifts in precipitation patterns, with some regions experiencing more intense rainfall while others face prolonged droughts [48]. These changes have profound implications for pavement performance and longevity. Heavy rainfall can saturate pavement layers, reducing their load-bearing capacity and increasing the risk of potholes and washouts (Figure 8). When pavements become waterlogged, the subgrade and other

pavement constituent layers (sub-base and base) materials weaken, leading to surface deformations such as rutting and potholes. This saturation not only diminishes the structural integrity of the pavement but also accelerates the deterioration process, especially in areas with inadequate drainage systems [49].

Prolonged wet conditions exacerbate these issues by continuously weakening the pavement structure. In regions with poor drainage, water can accumulate and infiltrate the pavement layers, leading to a loss of support in the subgrade and base layers [51]. This prolonged moisture exposure can cause stripping, where the bond between the asphalt binder and aggregate is weakened, reducing the cohesive properties of the pavement and making it more susceptible to damage [49]. Additionally, frequent and intense precipitation events can lead to increased incidences of flooding, further stressing the pavement infrastructure and necessitating more robust drainage solutions (Figure 9) [52].



Figure 7 Coastal road eroded by waves due to sea level rise [47]



Figure 8 Precipitation-induced pothole [50]



Figure 9 Precipitation-induced erosion [53]

Conversely, drought conditions pose their own set of challenges for pavement performance. Extended dry periods can lead to the drying and cracking of pavement surfaces, particularly in areas with expansive clay soils [54]. These soils shrink significantly when they lose moisture,

causing the pavement to settle and crack (Figure 10). This shrinkage creates pathways for water infiltration once the rain returns, leading to further deterioration. The combination of dry periods followed by heavy rainfall can be particularly damaging, as the dried and cracked soils



Figure 10 Shrinkage-induced pavement cracking [56]

are highly vulnerable to erosion and water damage [49]. Moreover, prolonged drought can lead to reduced soil moisture content, which impacts the underlying support layers, exacerbating pavement surface cracking and overall structural weakness [55].

Other Climatic Stressors

Beyond temperature and precipitation, climatic factors like solar radiation, wind, and humidity significantly impact pavement performance. Increased solar radiation exacerbates the urban heat-island effect, softening asphalt and accelerating UV-induced ageing, leading to rutting and cracking [57]-[58]. Changes in wind patterns deposit debris onto roadways, acting as abrasives that wear surfaces, reduce skid resistance, and increase safety hazards [59]. High winds also amplify temperature effects by accelerating evaporation, causing faster drying and cracking of pavement materials [60]. Humidity variations affect pavement strength and durability. High humidity promotes moisture absorption, reducing material stiffness, while low humidity increases brittleness, leading to cracking. Coastal areas face additional challenges from salt-laden environments that corrode pavements [61].

Adaptation and Mitigation Strategies

Given the diverse impacts of climate change on pavement performance across different regions, it is crucial to develop tailored adaptation and mitigation strategies. Adaptation measures should focus on enhancing the resilience of pavement structures to withstand the impacts of changing climatic conditions. Mitigation strategies should focus on reducing the carbon footprint of pavement construction and maintenance activities.

Adaptation Strategies

Several adaptation strategies have been proposed and implemented to address the impacts of climate change on pavement performance. These strategies can be broadly categorised into advanced materials and technologies, design adjustments, proactive maintenance practices, and mitigation measures.

Advanced Materials and Technologies

Polymer-modified asphalts and high-performance concrete offer better resistance to temperature extremes and moisture ingress, reducing the likelihood of rutting and cracking [22]. Anti-stripping agents prevent moisture-induced damage in regions prone to

heavy snowfall and freeze-thaw cycles by enhancing the bond between asphalt binder and aggregate [62]. Corrosion-resistant materials protect concrete pavements in coastal regions from salt-induced corrosion [63].

Design Adjustments

Increasing pavement thickness provides additional structural capacity to withstand heavier loads and environmental stresses, extending the service life of the pavement [22]. Reflective surfaces reduce heat absorption, mitigating the impact of high temperatures on pavement performance [15]. Enhanced drainage systems prevent water accumulation and manage surface runoff effectively during heavy rainfall events, including permeable pavements and well-designed subsurface drainage systems [52].

Proactive Maintenance Practices

Timely sealing of cracks prevents water infiltration, weakening the pavement structure and leading to further damage [64]. Regular resurfacing restores the pavement surface and addresses issues such as rutting and surface wear before they escalate. Predictive maintenance models use data analytics and sensor technologies to monitor pavement conditions in real-time and predict future deterioration, allowing for timely interventions [65].

Mitigation Measures

Mitigation measures in pavement construction focus on reducing environmental impact through innovative materials and technologies. Recycled materials, such as reclaimed asphalt pavement (RAP) and recycled concrete aggregate (RCA), conserve natural resources and reduce energy consumption and greenhouse gas emissions [66]. Warm-mix asphalt (WMA) technologies minimise energy use and emissions by enabling asphalt production and application at lower temperatures [67]. High-performance materials, including fibre-reinforced asphalts and concretes, enhance pavement strength and longevity [68].

Green infrastructure elements, such as vegetative swales and permeable pavements, help manage stormwater runoff and mitigate urban heat island effects [62]. Smart pavements with sensors provide real-time data on environmental conditions, traffic loads, and pavement performance, enabling optimised maintenance and traffic management [65].

Policy and Planning Considerations

Updating design codes and standards to integrate future climate projections ensures that infrastructure is resilient to evolving conditions. This involves adopting enhanced drainage systems, increased pavement thickness, and resilient materials [69]. For instance, the American Association of State Highway and Transportation Officials (AASHTO) Drainage Manual continues to rely on stationary Intensity–Duration–Frequency (IDF) curves derived from historical climate records, without guidance on adjusting for projected changes in precipitation extremes and associated flood risks [70]. Similarly, the AASHTO Mechanistic–Empirical Pavement Design Guide (MEPDG) does not mandate the use of climate projections in material selection and structural design, creating vulnerabilities to premature deterioration under shifting temperature and precipitation regimes [71]. At the structural level, Eurocode EN 1991-1-4 (Wind Actions) assumes climatic stationarity. It therefore omits consideration of increasing storm intensities, the potential for tropical cyclone intrusions, and evolving storm tracks, all of which could pose significant risks to bridge safety [72]. Investments in research and development foster innovation and accelerate the adoption of advanced technologies through collaborations among academia, industry, and government [73].

Knowledge dissemination and training empower transportation agencies to implement climate-resilient strategies. This includes guidelines for climate adaptation in pavement design and sharing case studies of successful implementations [69]. Broad stakeholder engagement ensures resource alignment and the integration of resilience measures across all stages of infrastructure development [74].

Case Studies and Regional Impacts

The impacts of climate change on pavements vary by region, necessitating context-specific adaptation and mitigation strategies.

Tropical Regions

Tropical areas experience challenges from high temperatures and heavy rainfall, leading to saturation, rutting, and accelerated asphalt ageing. Empirical studies in Malaysia and Taiwan indicate that road infrastructures are highly susceptible to rapid rutting and surface deterioration under frequent, intense rainfall and elevated temperatures. Although measures

such as porous pavements and enhanced drainage systems have been introduced, sustaining infiltration capacity remains challenging, and extreme precipitation events frequently exceed the design thresholds of these systems. The studies demonstrate the need for resilient materials and stormwater management systems, such as porous pavements, although maintaining infiltration rates remains challenging [75]–[77].

Arid Regions

Arid regions face extreme heat and prolonged droughts, which soften asphalt and cause cracking. Case studies from Iran and Arizona highlight rapid pavement deterioration, emphasising the use of flexible binders, such as polymer-modified asphalt and proactive maintenance to mitigate these effects. The studies noted that extreme heat continues to accelerate deterioration despite adaptation measures [78]–[80].

United Kingdom

Increased rainfall and flooding in the UK result in potholes, washouts, and accelerated material degradation. Improved drainage and resilient materials are crucial to address these challenges. Coastal pavements are particularly vulnerable to flooding and saltwater intrusion, necessitating innovative design approaches [49],[55]. In Lincolnshire County, for example, rural roads with shallow foundations on compressible soils show high rates of longitudinal cracking, edge failure, and uneven profiles due to ground movement exacerbated by climate-driven changes in water content. Current measures include avoiding traditional overlays that add weight and exacerbate compression issues, and implementing mesh reinforcement to ensure roads move as a single entity, reducing surface cracks [81]. However, techniques like mesh reinforcement pose a challenge for future resurfacing and utility work on the road network.

Southwestern United States

Prolonged drought and heat exacerbate cracking and surface degradation. Studies in Arizona and New Mexico underscore the importance of flexible asphalt binders and preventive maintenance strategies to mitigate the impacts of extreme conditions [55],[79]. Current mitigation measures include crack sealing and resurfacing, but extreme heat and drought outpace repair measures [82].

Australia

Urban areas with poor drainage systems in Australia suffer rapid pavement deterioration due to precipitation variability. Case studies highlight the importance of effective drainage solutions in urban planning. Additionally, bushfires cause significant damage to pavement surfaces and underlying structures, emphasising the need for heat-resistant materials [83]. Studies show that bushfire-prone rural roads in Victoria will face a 100% increase in direct and indirect costs from bushfire and rainfall-induced slope failures by 2070. Mitigation measures currently employed include enhanced slope risk analysis, debris removal, and slope stabilisation to address bushfire and post-fire landslide risks. These measures are limited mainly in the long term as an increase in the frequency of bushfires and the resultant extended closures of roads continue [84].

Coastal Regions

Coastal environments present challenges such as saltwater corrosion and high humidity. Studies in Florida and the US demonstrate that corrosion-resistant materials and protective coatings improve durability.

Sea-level rise and coastal flooding necessitate innovative design and adaptation strategies to protect coastal road infrastructure [61],[85].

Despite progress in understanding the impacts of climate change on pavement performance, further research is needed in key areas (Table 2). Future studies should focus on innovative materials and technologies, such as nano-modified asphalt binders, which could improve durability and resistance under extreme climatic conditions [86]. Long-term studies are essential to evaluate the effects of climate change on flexible, rigid, and composite pavements and to develop region-specific adaptation strategies [33].

Comprehensive life cycle cost analyses are vital for assessing the economic viability of adaptation measures, enabling informed decisions about infrastructure investments. These analyses will help policymakers and engineers prioritise cost-effective interventions for resilience and sustainability [87]. Enhanced collaboration between researchers, industry practitioners, and policymakers is crucial to translating

Table 2 Recommendations for future research directions

Research Area	Research Questions	Hypotheses
Impact of Nano-Modified Asphalt Binders	How do nano-modified asphalt binders perform under extreme climatic conditions, such as high temperatures and heavy rainfall?	Nano-modified asphalt binders will exhibit enhanced durability and resistance to rutting and cracking compared to traditional asphalt binders.
Long-Term Effects of Climate Change on Pavements	What are the long-term effects of climate change on different types of pavements, including flexible, rigid, and composite pavements?	Climate change will lead to accelerated deterioration of flexible pavements in tropical regions and increased cracking and ravelling in arid regions.
Region-Specific Adaptation Strategies	How can region-specific adaptation strategies be developed to mitigate the impacts of climate change on pavement performance?	Region-specific adaptation strategies, such as the use of corrosion-resistant materials in coastal regions and improved drainage systems in tropical regions, will enhance pavement resilience.
Comprehensive Life Cycle Cost Analyses	What are the economic viability and cost-benefit ratios of various adaptation measures for pavement infrastructure?	Comprehensive life cycle cost analyses will reveal that certain adaptation measures, such as the use of recycled materials and sustainable construction practices, offer the highest returns in terms of resilience and sustainability.
Advanced Data Analytics and Machine Learning Techniques	How can advanced data analytics and machine learning techniques enhance the predictive modelling of pavement performance under varying climatic conditions?	Leveraging advanced data analytics and machine learning techniques will improve the accuracy of predictive models, enabling more effective proactive maintenance and management strategies.

findings into actionable solutions. Interdisciplinary research centres and networks can drive innovation and knowledge sharing in pavement engineering and climate resilience [88]. Advanced data analytics and machine learning also offer potential to improve predictive modelling of pavement performance, aiding proactive maintenance strategies [65].

Key research areas include evaluating nano-modified asphalt binders under extreme conditions, hypothesising improved durability compared to traditional binders, and assessing climate change’s accelerated deterioration effects on different pavement types. Developing region-specific strategies, such as corrosion-resistant materials for coastal areas and improved drainage for tropical regions, is essential. Comprehensive life cycle cost analyses should highlight

cost-effective measures like recycled materials and sustainable construction practices for resilience and sustainability.

Policymakers should support adaptation strategies, foster innovation, and enhance collaboration, while practitioners should integrate these strategies into design and maintenance, adopt new technologies, and leverage data analytics for optimisation.

DISCUSSION

The review highlights the significant impact of climate change on pavement performance, emphasising temperature fluctuations and changes in precipitation patterns (Table 3). Rising global temperatures and erratic precipitation expose pavements to extreme

Table 3 Impacts of climate change on pavement performance and adaptation strategies

Climate Factor	Impact on Pavement	Future Research Areas	Practical Applications
High Temperatures	Softening of asphalt, leading to rutting and deformation	Developing resilient materials like nano-modified asphalt binders [86]	Using more flexible asphalt binders in hot regions [55]
Extreme Cold	Cracking and brittleness of pavement materials	Exploring innovative materials such as fibre-reinforced asphalts [86]	Incorporating resilient materials into pavement design [89]-[90]
Freeze-Thaw Cycles	Surface damage, potholes and structural failures	Improving predictive models using advanced data analytics [65]	Enhancing maintenance strategies to address freeze-thaw impacts [49]
Increased Rainfall	Saturation of pavement layers, weakening the load-bearing capacity	Studying the effectiveness of sustainable drainage solutions [52]	Implementing permeable pavements and vegetative swales [22]
	Increased risk of potholes and washouts	Conducting life cycle cost analyses of adaptation strategies [87]	Improving drainage systems to manage increased precipitation [49]
Prolonged Wet Conditions	Accelerated material degradation, especially in poor drainage areas	Developing standardised methodologies for assessing adaptation strategies [87]	Prioritising drainage improvements in wet regions [22]
Drought Conditions	Drying and cracking of pavement surfaces, materials in pavement compromising structural integrity.	Exploring the use of recycled materials in pavement construction [87]	Adopting more flexible asphalt binders in arid regions [55]
Increased Solar Radiation	Contribution to the urban heat island effect, accelerating material breakdown	Integrating climate projections into asset management systems [91]	Using reflective surfaces to reduce heat absorption [15]
Wind Patterns	Influence on the distribution of dust and debris, impacting road surface conditions	Fostering international collaboration and knowledge exchange [88]	Implementing smart infrastructure technologies to monitor conditions [65]
Humidity Variations	Pavement materials, altering strength and durability	Offering education and training programs on climate-resilient engineering [88]	Selecting materials appropriate for local humidity levels [62]

weather, accelerating deterioration and escalating maintenance costs. Temperature variations, including extreme heat and cold, lead to issues like rutting, deformation, and cracking. Freeze-thaw cycles worsen this by causing repeated expansion and contraction of pavement materials, resulting in potholes and structural damage. Advanced materials, such as polymer-modified asphalts, have shown promise in enhancing durability under such conditions [83],[90].

Precipitation changes also pose challenges, with increased rainfall weakening pavement layers and prolonged wet conditions accelerating degradation, especially in areas with inadequate drainage. Conversely, droughts cause drying and cracking, compromising structural integrity [49]. Adaptation strategies like enhanced drainage systems and permeable pavements are crucial [52]. Other stressors, including solar radiation, wind, and humidity, exacerbate these impacts by affecting material properties and pavement durability [92]. Regional climate variations demand tailored strategies to address specific challenges effectively.

Implications for Future Research and Practice

Future research should focus on developing climate-resilient materials, such as nano-modified and fibre-reinforced asphalts, which offer greater durability under extreme weather conditions [86]. Improved predictive models using data analytics and machine learning can provide insights into potential climate impacts, aiding in proactive maintenance and adaptation strategies [65]. Through comprehensive life cycle cost analyses, studies should also evaluate the effectiveness and economic viability of adaptation measures, such as recycled materials and sustainable construction [87].

Practical guidelines and standardised methodologies are needed to help practitioners incorporate climate considerations into their work. These should reflect best practices and enable reliable evaluations of adaptation strategies. Collaborative research initiatives and interdisciplinary approaches are essential to drive innovation and knowledge exchange [88].

Limitations of Current Research

Most studies are region-specific, making generalising findings across diverse climates challenging. Long-term studies are needed to capture the full impacts of climate change on pavements, including monitoring environmental and material performance trends over decades [33]. Additionally, a lack of standardised frameworks for assessing adaptation strategies hinders direct comparisons. Enhanced collaboration among researchers, industry, and policymakers is necessary to address these gaps [88].

Practical Applications and Policy Implications

Case studies illustrate the value of region-specific adaptation strategies, such as flexible asphalt binders for extreme heat in the southwestern US [55], corrosion-resistant materials in coastal Florida [61], and advanced drainage systems in Australia and the UK to mitigate increased rainfall [22],[49]. Policymakers should integrate climate resilience into infrastructure planning, update design codes to reflect climate projections, and fund innovative research and training [73]-[74]. Collaborative planning among stakeholders ensures climate resilience is embedded in all infrastructure development stages, promoting sustainable and adaptive practices [74],[88].

Table 4 shows strategic recommendations for both policymakers and practitioners to strengthen pavement resilience under climate change impacts.

Table 4 Key recommendations for policymakers and practitioners in enhancing pavement resilience and adaptation strategies

Recommendation	Policymakers	Practitioners
Develop Region-Specific Adaptation Strategies	Prioritise the development of region-specific adaptation strategies to address the unique challenges faced by different regions.	Incorporate these strategies into pavement design and maintenance practices.
Invest in Innovative Materials and Technologies	Support research and development of innovative materials and technologies that enhance pavement resilience.	Adopt these technologies in their projects to improve pavement performance.
Enhance Collaboration and Knowledge Exchange	Establish interdisciplinary research centres and networks to facilitate knowledge exchange and innovation in pavement engineering and climate resilience.	Participate in these networks to stay updated on the latest research and best practices.
Prioritise Proactive Maintenance Strategies	Encourage the use of advanced data analytics and machine learning techniques to enhance predictive modelling and proactive maintenance strategies.	Adopt these techniques to optimise maintenance schedules and improve pavement performance.
Evaluate the Economic Viability of Adaptation Measures	Conduct comprehensive life cycle cost analyses to evaluate the economic viability of various adaptation measures.	Use these analyses to inform their decisions regarding infrastructure investments and maintenance practices.

CONCLUSION

Climate change profoundly affects pavement performance, necessitating innovative, integrated approaches to enhance resilience and sustainability. Developing advanced materials, such as nano-modified asphalts and fibre-reinforced concrete, alongside adopting adaptive design practices, is vital for mitigating the effects of extreme weather conditions. Smart pavements equipped with sensors can monitor environmental conditions and traffic loads, enabling the implementation of data-driven maintenance and management strategies. Integrating climate considerations into asset management systems prioritises maintenance based on vulnerability, ensuring efficient resource allocation. In infrastructure designs, incorporating renewable energy solutions, such as solar panels and wind turbines, offers opportunities to reduce the carbon footprint of transportation networks. Education and training programs focused on climate resilience for engineers and planners are critical for fostering innovation and equipping practitioners with the latest tools and best practices. International collaboration through conferences, research partnerships, and knowledge-sharing networks will accelerate global progress in addressing climate impacts. Policymakers must update design codes to reflect climate projections, mandate the use

of resilient materials, and support the development of enhanced drainage systems. Investments in research, pilot studies, and life cycle assessments will guide effective strategies and informed decisions.

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REFERENCES

- [1] H. Vajjarapu, A. Verma, and S. Gulzar, "Adaptation Policy Framework for Climate Change Impacts on Transportation Sector in Developing Countries," *Transp Dev Econ*, vol. 5, p. 3, 2019, doi: 10.1007/s40890-019-0071-y.
- [2] A. Albayati, "A review of rutting in asphalt concrete pavement," *Open Eng.*, vol. 13, no. 1, p. 20220463, 2023, doi: 10.1515/eng-2022-0463.
- [3] J.R. Olsen, "Adapting infrastructure and civil engineering practice to a changing climate," in *Adapting Infrastructure and Civil Engineering Practice to a Changing Climate*, 2015, doi: 10.1061/9780784479193.

- [4] A.M. Stoner, J.S. Daniel, J.M. Jacobs, K. Hayhoe, and I. Scott-Fleming, "Quantifying the impact of climate change on flexible pavement performance and lifetime in the United States," *Transp. Res. Rec.*, vol. 2673, no. 1, Art. no. 1, 2019.
- [5] T. Ahmad and H. Khawaja, "Review of Low-Temperature Crack (LTC) Developments in Asphalt Pavements," *Int. J. Multiphysics*, vol. 12, no. 2, pp. 169–188, 2018, doi: 10.21152/1750-9548.12.2.169.
- [6] L. Moretti and G. Loprencipe, "Climate Change and Transport Infrastructures: State of the Art," *Sustainability*, vol. 10, p. 4098, 2018, doi: 10.3390/su10114098.
- [7] R. Asariotis, "Climate change impacts and adaptation for coastal transportation infrastructure: a sustainable development challenge for SIDS in the Caribbean and Beyond," *Coastal and Marine Environments*, 2020, pp. 253–264, doi: 10.1201/9780429441004-29.
- [8] I.M. Picketts, J. Andrey, L. Matthews, and K. Keller, "Climate change adaptation strategies for transportation infrastructure in Prince George, Canada," *Reg. Environ. Change*, vol. 16, no. 4, pp. 1109–1120, 2016, doi: 10.1007/s10113-015-0828-8.
- [9] M.S. Chowdhury, "Quantifying the Effects of Climate Change on Pavement Performance Prediction Using AASHTOWare Pavement ME Design," M.S. thesis, Dept. of Civil Engineering, Boise State Univ., Boise, ID, USA, 2020.
- [10] M.B. Regmi and S. Hanaoka, "A survey on impacts of climate change on road transport infrastructure and adaptation strategies in Asia," *Transp. Infrastruct. Geotechnol.*, 2011, doi: 10.1007/s10018-010-0002-y.
- [11] B.A.D. Almeida and A. Mostafavi, "Resilience of infrastructure systems to sea-level rise in coastal areas: Impacts, adaptation measures, and implementation challenges," *J. Infrastruct. Syst.*, vol. 22, no. 4, p. 04016014, 2016, doi: 10.1061/(ASCE)IS.1943-555X.0000326A1.
- [12] P.P. Gudipudi, B.S. Underwood, and A. Zalgout, "Impact of climate change on pavement structural performance in the United States," *Transp. Res. Part Transp. Environ.*, vol. 57, pp. 172–184, Dec. 2017, doi: 10.1016/j.trd.2017.09.022.
- [13] M. Hasnain, "Effects of climate change on road infrastructure and development of adaptation measures," *Int. J. Sustain. Built Environ.*, vol. 6, no. 1, pp. 169–177, 2017, doi: 10.1016/j.ijsbe.2017.01.004.
- [14] J.S. Cañavera Herrera, "Roads to adaptation: Understanding adaptation planning of urban road infrastructure," Ph.D. dissertation, Univ. of Cambridge, Cambridge, U.K., 2019. [Online]. Available: <https://doi.org/10.17863/CAM.50346>
- [15] J.F. Knott, J.M. Jacobs, J.E. Sias, P. Kirshen, and E.V. Dave, "A framework for introducing climate-change adaptation in pavement management," *Sustainability*, vol. 11, no. 16, Art. no. 16, 2019.
- [16] Y. Qiao, J. Santos, A.M.K. Stoner, and G. Flinstch, "Climate change impacts on asphalt road pavement construction and maintenance: An economic life cycle assessment of adaptation measures in the State of," *J. Ind. Ecol.*, pp. 342–355, 2019, doi: 10.1111/jiec.12936.
- [17] A. Hemed, L. Ouadif, L. Bahi, and A. Lahmili, "Impact of climate change on pavements," *Int. J. Pavement Eng.*, vol. 21, no. 8, pp. 999–1015, 2020.
- [18] Y. Andersson-Sköld, L. Nordin, E. Nyberg, and M. Johannesson, "A framework for identification, assessment and prioritisation of climate change adaptation measures for roads and railways," *Int. J. Environ. Res. Public Health*, vol. 18, no. 23, p. 12314, 2021, doi: 10.3390/ijerph182312314.
- [19] K. E. Haslett et al., "Climate change impacts on flexible pavement design and rehabilitation practices," *Road Mater. Pavement Des.*, vol. 22, no. 9, pp. 2098–2112, 2021.
- [20] S.T. Swarna, "Influence of climate change on pavement design and materials in Canada," Ph.D. dissertation, Dept. of Civil Engineering, Memorial Univ. of Newfoundland, St. John's, NL, Canada, 2021. [Online]. Available: <https://memorial.scholaris.ca/items/c73ddbdf-de30-4d81-bf00-e1061f97c0fe>
- [21] A. Almeida and L. Picado-Santos, "Asphalt road pavements to address climate change challenges—An overview," *Appl. Sci.*, vol. 12, no. 24, p. 12515, 2022, doi:10.3390/app122412515.
- [22] M. Saleh and L. Hashemian, "Addressing Climate Change Resilience in Pavements: Major Vulnerability Issues and Adaptation Measures," *Sustainability*, 2022, doi: 10.3390/su14042410.
- [23] C. Chen, Y. Deng, M. Li, and X. Shi, "Investigation of key climatic factors affecting asphalt pavement roughness in different climate regions," *Transp. Res. Part Transp.*

- Environ.*, vol. 122, p. 103877, Sep. 2023, doi: 10.1016/j.trd.2023.103877.
- [24] IPCC, "Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," IPCC, Geneva, Switzerland, Rep. 5AR-SYR, 2014. Accessed: Sept. 16, 2024. [Online]. Available: <https://www.ipcc.ch/report/ar5/syr/>
- [25] M. Hulme, "On the origin of 'the greenhouse effect': John Tyndall's 1859 interrogation of nature," *Weather*, p. 64, 2009, doi: 10.1002/WEA.386.
- [26] L.C. Harris, D.J. Smith, and E.J. Wilson, "Ocean acidification and coral reefs: Recent advances in understanding impacts and adaptations," *Nat. Clim. Change*, vol. 13, no. 4, pp. 344–353, 2023, doi: 10.1038/s41558-023-01447-7.
- [27] N. Raffio, "Brutal heatwave sparks wildfires across California," *USC Today*. Accessed: Sep. 19, 2025. [Online]. Available: <https://today.usc.edu/brutal-heatwave-sparks-wildfires-across-california/>
- [28] A. Raza, A. Razzaq, S.S. Mehmood, X. Zou, X. Zhang, Y. Lv, and J. Xu, "Impact of climate change on crops adaptation and strategies to tackle its outcome: A review," *Plants*, vol. 8, no. 2, p. 34, 2019, doi: 10.3390/plants8020034.
- [29] M. Franchini and P. Mannucci, "Impact on human health of climate changes," *Eur. J. Intern. Med.*, vol. 26 1, pp. 1–5, 2015, doi: 10.1016/j.ejim.2014.12.008.
- [30] WHO, "Climate change and health." *World Health Organization*, 2021. [Online]. Available: <https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health>
- [31] I. Gabol, "Lahore tops global pollution chart again as govt tries to tackle crisis," *Dawn*. Accessed: Sep. 19, 2025. [Online]. Available: <https://www.dawn.com/news/1872321>
- [32] N.R. Kabange, Y. Kwon, S.-M. Lee, J.-W. Kang, J.-K. Cha, H. Park, G.D. Dzorokpe, D. Shin, K.W. Oh, and J.-H. Lee, "Mitigating greenhouse gas emissions from crop production and management practices, and livestock: A review," *Sustainability*, vol. 15, no. 22, p. 15889, 2023, doi: 10.3390/su152215889
- [33] Y. Qiao, J. Santos, A.M. Stoner, and G. Flinstch, "Climate change impacts on asphalt road pavement construction and maintenance: An economic life cycle assessment of adaptation measures in the State of Virginia, United States," *J. Ind. Ecol.*, vol. 24, no. 2, pp. 342–355, 2020.
- [34] UNFCCC, "What is the United Nations Framework Convention on Climate Change?" *United Nations Climate Change*, 2021. [Online]. Available: <https://unfccc.int/process/the-convention/what-is-the-united-nations-framework-convention-on-climate-change>
- [35] IPCC, "Sixth Assessment Report — IPCC," IPCC. Accessed: Sep. 16, 2024. [Online]. Available: <https://www.ipcc.ch/assessment-report/ar6/>
- [36] A. Albayati and A. Alani, "Influence of Temperature Upon Permanent Deformation Parameters of Asphalt Concrete Mixes," *J. Eng.*, 2017, doi: 10.31026/j.eng.2017.07.02.
- [37] M. J. Koetse and P. Rietveld, "The impact of climate change and weather on transport: An overview of empirical findings," *Transp. Res. Part Transp. Environ.*, vol. 14, no. 3, pp. 205–221, May 2009, doi: 10.1016/j.trd.2008.12.004.
- [38] M.G. Al-Taher, A.M. Sawan, M.E.-S.A. Solyman, M.I. El-Sharkawi Attia, and M.F. Ibrahim, "Evaluating the Durability of Asphalt Mixtures for Flexible Pavement Using Different Techniques: A Review," *Int. J. Pavement Res. Technol.*, 2024, doi: 10.1007/s42947-024-00469-1.
- [39] N. Matini, S. Gulzar, S. Underwood, and C. Castorena, "Evaluation of Structural Performance of Pavements under Extreme Events: Flooding and Heatwave Case Studies," *Transp. Res. Rec.*, vol. 2676, no. 7, pp. 233–248, Jul. 2022, doi: 10.1177/03611981221077984.
- [40] "12 Types Of Cracks In Asphalt Pavement: Symptoms, Causes And Treatment Of Defects," *Civil Engineering Profile*. Accessed: Sep. 19, 2025. [Online]. Available: <https://civilengpro.com/12-types-of-cracks-in-asphalt-pavement/>
- [41] J. Fu and A. Shen, "Meso- and Macro-Mechanical Analysis of the Frost-Heaving Effect of Void Water on Asphalt Pavement," *Materials*, vol. 15, 2022, doi: 10.3390/ma15020414.
- [42] W. Si, B. Ma, N. Li, J. Ren, and H. Wang, "Reliability-based assessment of deteriorating performance to asphalt pavement under freeze–thaw cycles in cold regions,"

Constr. Build. Mater., vol. 68, pp. 572–579, 2014, doi: 10.1016/J.CONBUILDMAT.2014.07.004.

- [43] B. Paving, "How to Prevent Erosion on a Chip Seal Driveway." *Boswell's Asphalt Paving*, Accessed: Sep. 19, 2025. [Online]. Available: <https://boswellspaving.com/how-to-prevent-erosion-on-a-chip-seal-driveway-effective-tips-and-strategies/>
- [44] R. Lindsey and L. Dahlman, "Climate Change: Global Temperature, NOAA *Climate.gov*." Accessed: Sep. 17, 2024. [Online]. Available: <http://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature>
- [45] A. Shepherd and D. Wingham, "Recent Sea-Level Contributions of the Antarctic and Greenland Ice Sheets," *Science*, vol. 315, pp. 1529–1532, 2007, doi: 10.1126/science.1136776.
- [46] J. Pulliainen et al., "Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018," *Nature*, vol. 581, pp. 294–298, 2020, doi: 10.1038/s41586-020-2258-0.
- [47] "4 Ways Climate Change Is Already Taking a Toll," *Discover Magazine*. Accessed: Sep. 19, 2025. [Online]. Available: <https://www.discovermagazine.com/4-ways-climate-change-is-already-taking-a-toll-43754>
- [48] K. Trenberth, "Changes in precipitation with climate change," *Clim. Res.*, vol. 47, pp. 123–138, 2011, doi: 10.3354/CR00953.
- [49] A. Abouelsaad and G. White, "Review of Asphalt Mixture Ravelling Mechanisms, Causes and Testing," *Int J Pavement Res Technol*, vol. 15, pp. 1448–1462, 2022, doi: 10.1007/s42947-021-00100-7.
- [50] "Road Safety: What Elements Can Make a Road Safe?" *Blyncsy*, Accessed: Sep. 19, 2025. [Online]. Available: <https://blyncsy.com/safety/road-safety-elements-road-safe/>
- [51] M. A. Ghasia, Y. U. Shah, and V. Rotte, "A critical review on evaluation of pavement drainage systems," in *Lecture Notes in Civil Engineering: Geotechnics for Transportation Infrastructure*, R. Sundaram, J. Shahu, and V. Havanagi, Eds. Singapore: Springer, 2019, vol. 28, doi: 10.1007/978-981-13-6701-4_5
- [52] D. Lu, S. Tighe, and W. Xie, "Impact of flood hazards on pavement performance," *Int. J. Pavement Eng.*, vol. 21, pp. 746–752, 2018, doi: 10.1080/10298436.2018.1508844.
- [53] "Ten Key Facts to Know About Federal Disaster Assistance," *HSToday*, Accessed: Sep. 19, 2025. [Online]. Available: <https://www.hstoday.us/subject-matter-areas/emergency-preparedness/ten-key-facts-to-know-about-federal-disaster-assistance/>
- [54] A. Puppala, T. Manosuthkij, S. Nazarian, and L. Hoyos, "Threshold moisture content and matric suction potentials in expansive clays prior to initiation of cracking in pavements," *Can. Geotech. J.*, vol. 48, pp. 519–531, 2011, doi: 10.1139/T10-087.
- [55] M. Hedayati and S. Hossain, "Data based model to estimate subgrade moisture variation case study: Low volume pavement in North Texas," *Transp. Geotech.*, vol. 3, pp. 48–57, 2015, doi: 10.1016/J.TRGEO.2015.03.001.
- [56] "The Lifecycle of Asphalt," *Aegis Asphalt Construction*. Accessed: Sep. 19, 2025. [Online]. Available: <https://aegisasphalt.com/the-lifecycle-of-asphalt/>
- [57] H. Yu, X. Bai, G. Qian, H. Wei, X. Gong, J. Jin, and Z. Li, "Impact of ultraviolet radiation on the aging properties of SBS-modified asphalt binders," *Polymers*, vol. 11, no. 7, p. 1111, 2019, doi: 10.3390/polym11071111.
- [58] A. Azarhoosh and M. Koohmishi, "Investigation of the rutting potential of asphalt binder and mixture modified by styrene-ethylene/propylene-styrene nanocomposite," *Constr. Build. Mater.*, vol. 255, p. 119363, 2020, doi: 10.1016/j.conbuildmat.2020.119363.
- [59] A. Bhattachan, G. Okin, J. Zhang, S. Vimal, and D. Lettenmaier, "Characterising the Role of Wind and Dust in Traffic Accidents in California," *GeoHealth*, vol. 3, pp. 328–336, 2019, doi: 10.1029/2019GH000212.
- [60] A. Gadalla, "The effects of extreme weather events on flexible pavement," B.Eng. Honours dissertation, Univ. of Southern Queensland, Faculty of Health, Engineering and Sciences, Toowoomba, QLD, Australia, Oct. 2020. [Online]. Available: https://sear.unisq.edu.au/43066/13/Gadalla_A_Nataatmadja_Redacted.pdf
- [61] K. Zhang, W. Li, and F. Han, "Performance deterioration mechanism and improvement techniques of asphalt mixture in salty and humid environment," *Constr. Build. Mater.*, 2019, doi: 10.1016/J.CONBUILDMAT.2019.03.061.

- [62] C. Zhu, J. Tang, H. Zhang, and H. Duan, "Effect of liquid anti-stripping agents on moisture sensitivity of crumb rubber modified asphalt binders and mixtures," *Constr. Build. Mater.*, 2019, doi: 10.1016/J.CONBUILDMAT.2019.07.173.
- [63] K. Nguyen, J. Lee, K. Lee, and N. Ahn, "An Experimental Study of the Effects of Chloride Ions on the Corrosion Performance of Polymer Coated Rebar in Concrete Pavement," *J. Asian Archit. Build. Eng.*, vol. 11, pp. 111–117, 2012, doi: 10.3130/jaabe.11.111.
- [64] R.M. Mousa and M.A. Elseifi, "Optimal application timing and cost effectiveness of crack sealing in asphalt concrete overlays in Louisiana," in *Tran-SET 2020*, pp. 34–48, 2020, doi: 10.1061/9780784483305.005.
- [65] A. Al-Mansour, K. Lee, and A. Al-Qaili, "Prediction of Pavement Maintenance Performance Using an Expert System," *Appl. Sci.*, 2022, doi: 10.3390/app12104802.
- [66] J. Fournier, D. Álvarez, A. Aenlle, A. Tenza-Abril, and S. Ivorra, "Combining Reclaimed Asphalt Pavement (RAP) and Recycled Concrete Aggregate (RCA) from Cuba to Obtain a Coarse Aggregate Fraction," *Sustainability*, vol. 12, p. 5356, 2020, doi: 10.3390/su12135356.
- [67] T. Mattinzioli, M. Sol-Sánchez, A. Carrión, F. Moreno-Navarro, M. Rubio-Gámez, and G. Martínez, "Analysis of the GHG savings and cost-effectiveness of asphalt pavement climate mitigation strategies," *J. Clean. Prod.*, vol. 320, p. 128768, 2021, doi: 10.1016/J.JCLEPRO.2021.128768.
- [68] A. Karmacharya and S. Chao, "Precast Ultra-High-Performance Fiber-Reinforced Concrete (UHP-FRC) for Fast and Sustainable Pavement Repair," *MATEC Web of Conferences*, 2019, doi: 10.1051/MATECCONF/201927101004.
- [69] A. Amir, B. Amir, A. Alghannam, T. Abdeen, A. Al-Howaish, R. Alsheniber, A. Al-Mulhim, and D. Alfaraj, "Analysis of road traffic injuries presented to the emergency department in the Eastern Province of Saudi Arabia: a hospital-based study," *J. Med. Life*, vol. 16, pp. 1825– 1838, 2023, doi: 10.25122/jml-2023-0316.
- [70] M. Jiménez-U, L. E. Peña, and J. López, "Non-stationary analysis for road drainage design under land-use and climate change scenarios," *Heliyon*, vol. 8, 2022. doi: 10.1016/j.heliyon.2022.e08942.
- [71] S. Underwood, Z. Guido, P. Gudipudi, and Y. Feinberg, "Increased costs to US pavement infrastructure from future temperature rise," *Nature Climate Change*, vol. 7, pp. 704–707, 2017, doi: 10.1038/NCLIMATE3390.
- [72] V. Mishra and A. Sadhu, "Towards the effect of climate change in structural loads of urban infrastructure: A review," *Sustainable Cities and Society*, 2022. [Online]. Available: <https://doi.org/10.1016/j.scs.2022.104352>
- [73] Z. You, M. Hamzah, H. Wang, A. Diab, and Q. Dai, "Advanced Pavement Materials for Sustainable Transportation Infrastructure," *Adv. Mater. Sci. Eng.*, pp. 1–1, 2018, doi: 10.1155/2018/3175651.
- [74] G. Filosa, A. Plovnick, L. Stahl, R. Miller, and D.H. Pickrell, "Vulnerability assessment and adaptation framework, third edition," John A. Volpe Nat. Transp. Syst. Center, Cambridge, MA, USA, Rep. DOT-VNTSC-FHWA-18-04; FHWA-HEP-18-020, 2017. [Online]. Available: <https://rosap.ntl.bts.gov/view/dot/36188>
- [75] W. Zeng, S. Wu, J. Wen, and Z. Chen, "The temperature effects in aging index of asphalt during UV aging process," *Constr. Build. Mater.*, vol. 93, pp. 1125–1131, 2015.
- [76] H. Yaacob, M.R. Hainin, A. Safuan, and L.C. Fung, "Information for the Malaysian asphalt industry towards better pavement interlayer bonding," *Sains Malays.*, vol. 43, no. 3, pp. 467– 474, 2014.
- [77] Y.-Y. Cheng, S.-L. Lo, C.-C. Ho, J.-Y. Lin, and S. L. Yu, "Field Testing of Porous Pavement Performance on Runoff and Temperature Control in Taipei City," *Water*, vol. 11, no. 12, Art. no. 12, 2019, doi: 10.3390/w11122635.
- [78] A. Mahpour and T. El-Diraby, "Incorporating Climate Change in Pavement Maintenance Policies: Application to Temperature Rise in the Isfahan County, Iran," *Sustain. Cities Soc.*, vol. 71, p. 102960, Aug. 2021, doi: 10.1016/j.scs.2021.102960.
- [79] F.A. Schneider, J.C. Ortiz, J.K. Vanos, D.J. Sailor, and A. Middel, "Evidence-based guidance on reflective pavement for urban heat mitigation in Arizona," *Nat. Commun.*, vol. 14, no. 1, p. 1467, 2023, doi: 10.1038/s41467-023-36972-5.
- [80] P. Jaskula and J. Judycki, "Durability of asphalt concrete subjected to deteriorating effects of water and frost," *J. Perform. Constr. Facil.*, vol. 30, no. 1, p. 4014004, 2016.

- [81] A. Harrison, M. Heaton, and D. Entwisle, "Increasing road network resilience to the impacts of ground movement due to climate change – A case study from Lincolnshire, United Kingdom," *Quarterly Journal of Engineering Geology and Hydrology*, 2023, doi: 10.1144/qjehg2023-002
- [82] V.H.S. de Abreu, A.S. Santos, and T.G.M. Monteiro, "Climate Change Impacts on the Road Transport Infrastructure: A Systematic Review on Adaptation Measures," *Sustainability*, vol. 14, no. 14, 2022, doi: 10.3390/su14148864
- [83] S. Setunge, P. Mendis, K. Karunasena, K. Zhang, D. Amaratunga, W. Lokuge, N. Herath, L. Shi, and H. Mohseni, "Enhancing resilience of critical road structures: bridges, culverts and floodways under natural hazards: final project report," *The National Academies of Sciences, Engineering, and Medicine*, 2021, Accessed: Oct. 17, 2024. [Online]. Available: <https://trid.trb.org/View/2365003>
- [84] T. Mote and J. Hellmuth, "Enhancing resilience by considering climate change influenced bushfire in slope risk analysis," *Australian Geomechanics Journal*, 2024, doi: 10.56295/agj5938
- [85] C.M. Palinkas, P. Orton, M.A. Hummel, ... W. Veatch, and T. Williams, "Innovations in Coastline Management With Natural and Nature-Based Features (NNBF): Lessons Learned From Three Case Studies," *Front. Built Environ.*, vol. 8, Apr. 2022, doi: 10.3389/fbuil.2022.814180.
- [86] E. Aflaki, M. Mojtahedi, H. R. Majidifard, and M. Ameri, "Nano-modified asphalt binders for enhanced pavement resilience," *J. Mater. Civ. Eng.*, vol. 33, no. 5, p. 04021005, 2021.
- [87] S. Dicker, S. Unsworth, R. Byrnes, B. Ward, M. Bhatt, and A. Paul, *Saving lives and livelihoods: The benefits of investments in climate change adaptation and resilience*. Leeds, UK: CCCEP, 2021.
- [88] A. Esmalian, F. Yuan, A.A. Rajput, ... C.-C. Lee, and C.-W. Hsu "Operationalising resilience practices in transportation infrastructure planning and project development," *Transp. Res. Part Transp. Environ.*, vol. 104, p. 103214, 2022, doi: 10.1016/j.trd.2022.103214.
- [89] A. Dawson, "Anticipating and responding to pavement performance as climate changes," in *Climate Change, Energy, Sustainability and Pavements*, K. Gopalakrishnan, W. Steyn, and J. Harvey, Eds. Berlin, Germany: Springer, 2014, doi: 10.1007/978-3-662-44719-2_4.
- [90] J. Zhang, Z. Yao, T. Yu, S. Liu, and H. Jiang, "Experimental evaluation of crumb rubber and polyethylene integrated modified asphalt mixture upon related properties," *Road Mater. Pavement Des.*, vol. 20, pp. 1413–1428, 2018, doi:10.1080/14680629.2018.1447505.
- [91] R. Hafezzadeh and A. Kavussi, "Application of micro-surfacing in repairing pavement surface rutting," *Road Mater. Pavement Des.*, vol. 22, pp. 1219–1230, 2019, doi: 10.1080/14680629.2019.1663243.
- [92] H. Zhu, M. Yu, J. Zhu, H. Lu, and R. Cao, "Simulation study on effect of permeable pavement on reducing flood risk of urban runoff," *Int. J. Transp. Sci. Technol.*, vol. 8, pp. 373–382, 2019, doi: 10.1016/J.IJTST.2018.12.001.