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Assessment of Erosion Influence on Asphalt Pavement of Kabul-Kandahar Highway

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Abstract

Erosion and deterioration are critical issues affecting asphalt pavements in Afghanistan. This study presents a comprehensive evaluation of the causes, impacts, and mitigation strategies for asphalt pavement erosion along the Kabul–Kandahar Highway. Using a mixed-methods approach, data were collected through field surveys, questionnaires completed by 103 technical experts and engineers, and laboratory testing of aggregate and asphalt samples. Statistical analysis revealed that pavement erosion is significantly accelerated by climate variability—particularly rainfall and temperature fluctuations—and by heavy vehicle traffic, poor drainage infrastructure, and substandard construction materials. Surface erosion was the most prevalent damage type, followed by cracking, potholing, rutting, and reflective cracking. The study recommends using high-quality modified binders, such as Styrene-Butadiene-Styrene asphalt, improving drainage systems, enhancing technical capacity, and integrating climate-resilient design principles to extend pavement service life and ensure long-term durability under challenging environmental conditions.

Keywords: Asphalt erosion, Climate change, Environmental impacts, Pavement deterioration, Road surface damage, Water and salt effects.

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Introduction

This research systematically evaluates the influence of asphalt pavement erosion in Afghanistan. As the country has been historically isolated from the sea and an importer of industrial technology in the region. Therefore, there is a serious need for better transportation and for the construction of asphalt and concrete roads, especially in urban areas. Due to the country's weak economic situation, it is important to construct roads in a way that minimizes the need for frequent repairs after asphalt deterioration, because maintenance and preservation also impose a financial burden on a country's budget. However, the most attention must be given from the beginning to ensure the selection of an environmentally compatible asphalt and to avoid future issues (Setiadji & Utomo, 2017).

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Given the strategic importance of the Kabul–Kandahar Highway as Afghanistan's primary national strip, understanding the instruments of erosion-induced asphalt deterioration along this route is essential. The interaction between climatic stressors, traffic loading, and material performance makes this highway particularly vulnerable to erosion-related pavement failures. Therefore, this study emphasizes analyzing erosion impacts along the Kabul–Kandahar Highway to support evidence-based maintenance and design decisions (Al-Atroush et al., 2022). The focus and targeted area of this research is the beginning and initial section of the Kabul-Kandahar highway, where unexpected weather conditions, including heavy rainfall, climate change, snow, freezing temperatures in winter, though various forms of asphalt pavements deterioration, such as Settlements, Potholes, Rutting, Fatigue cracks, Edge cracks, Block cracks, Reflection cracking and other types of surface degradation. Meanwhile, it should be noted that asphalt erosion refers to the deterioration, decay, and reduction in the quality of asphalt roads and streets, leading to surface irregularities and ultimately reducing vehicle safety (Bomers and Aguilar, 2018). The main causes of asphalt erosion are a mix of mechanical and environmental factors. Frequent traffic loading speeds up surface deterioration and adds to structural fatigue, particularly from heavier vehicles (Bukhariet et al., 2023). Moreover, inadequate drainage systems can allow water to seep into pavement layers, eroding the subgrade and lowering the asphalt's structural integrity (Aursand et al., 2013). Temperature variations, especially freeze-thaw cycles throughout the winter, cause the pavement to expand and contract, which can lead to layer separation and cracking. The rate of erosion is further increased by Low-quality materials and incorrect construction methods, leaving the asphalt more susceptible to premature deterioration (Ahmad & Khawaja, 2018).

In addition to affecting the physical condition of roads, asphalt deterioration also poses social and environmental challenges. Road accidents are more likely to occur due to surface imperfections and structural failures, putting lives at risk and disrupting daily travel (Chen et al., 2023).

Figure 1. *Deterioration of the Kabul-Kandahar highway (Google, 2019)*

Furthermore, poorly maintained roads increase fuel consumption and vehicle wear and tear, placing further financial strain on individual users and the national economy. In terms of the environment, deteriorating asphalt can cause contaminants to spread through runoff, particularly when rainfall carries loose particles into adjacent water bodies (Guo et al., 2024). Though asphalt erosion can lead to long-term infrastructure collapse if not strategically and promptly addressed, it can necessitate expensive rehabilitation rather than routine maintenance. Government budgets are severely strained by this, especially in resource-constrained developing countries like Afghanistan (Setiadji & Utomo, 2017).

Additionally, a stable strategy that includes both technological advancement and policy-level action is needed to combat asphalt erosion (Ji et al., 2017) .Warm-mix asphalt technology, fiber reinforcement, and polymer-modified binders can all greatly enhance pavement performance in challenging environmental conditions. At the same time, it is critical to implement policy changes that require regular inspection cycles, impose quality control throughout the building, and allot adequate funds for maintenance (Diouri et al., 2021). Even technically competent solutions could fail due to inadequate implementation or a lack of institutional commitment in the absence of such a dual approach (Guo et al., 2024). Asphalt erosion occurs due to natural and human-related factors. Natural factors are unexpected and occur under adverse weather conditions, causing damage to various parts of asphalt roads and leading to premature deterioration. They are described below.

- Temperature Variations and Weather Conditions: Cold temperatures and freezing conditions can cause asphalt to expand and contract, leading to surface cracking and further deterioration (Gao et al., 2023).
- Water and Moisture: The infiltration of rainwater and snow into asphalt cracks, followed by freezing, can cause fractures and further crack expansion. Groundwater seeping from lower layers can wash away the road base, leading to settlement and asphalt deterioration (Zou et al., 2023).
- Heavy Loads and Continuous Pressure: The movement of heavy vehicles such as trucks and buses exerts significant pressure on the asphalt pavement, resulting in cracking and gradual erosion (Gao et al., 2022).
- Wind Erosion and Pollution: Wind and dust can damage the road surface, particularly in areas where sand and fine particles erode the asphalt. Chemical pollutants, such as leaked oil and fuel from vehicles, degrade bitumen and weaken the asphalt structure (Jiang et al., 2022).
- Human factors are foreseeable outcomes resulting from the actions of road technical teams; in cases of negligence or improper practices, they can lead to asphalt road damage and deterioration. This could be described as follows:
- Low-Quality Raw Materials and Improper Asphalt Use: The use of substandard bitumen or incorrect material composition reduces asphalt durability. Moreover, if the road's substructure is not properly prepared, it can lead to subsidence and cracking (Huang et al., 2025).
- Lack of timely maintenance and repairs: If cracks, potholes, and road settlements are not repaired promptly, more severe damage will occur over time (Meng et al., 2024).
- Excessive load on roads: Roads designed for light vehicles may deteriorate more quickly when heavy loads frequently travel on them (Mehdinazar et al., 2024).
- Improper surface water drainage: Poorly designed road slopes and drainage systems result in surface water accumulation, causing significant damage to asphalt pavements (Meng et al., 2023).

- Asphalt failure due to erosion: Erosion of asphalt pavements is caused by various weather conditions, such as freezing, snow, rain, and dust, which ultimately result in different types of damage to asphalt pavements.

Potholes are mostly caused by water seeping into the pavement layers, which are repeatedly compressed by passing vehicles (Qiu et al., 2025). Surface depressions or cavities eventually form as a result of this process, which erodes the road surface's structural integrity. One of the main causes of asphalt pavement degradation is moisture infiltration. When water percolates through surface fissures and accumulates under the top layer, it reduces the materials' ability to bind and weakens the base's ability to support weight (Sapora et al., 2014). Freeze-thaw cycles, which produce expansion and contraction within the pavement structure, frequently accelerate this process in cold climates. Furthermore, pavement failure is exacerbated by dynamic loads from heavy traffic, as well as by environmental factors (Wang et al., 2021).

Frequent vehicle stress, particularly from trucks and buses, accelerates the deterioration of weak areas, transforming small surface defects into large depressions. Moreover, if these defects are not addressed promptly through maintenance, they may spread rapidly over time, endangering public safety and increasing repair costs (Tang et al., 2024). Pothole formation can be prevented by using high-quality construction materials and proper road design. Water-resistant layers, such as waterproof membranes, and surface treatments that prevent cracking can greatly extend pavement lifespan (Ahmad & Khawaja, 2018).

***Figure 2**. Potholes deterioration (Ahmad & Khawaja, 2018).*

Edge cracks, as seen in Figure 3, are frequently observed in cold locations. These cracks usually appear as long, arching fractures along the pavement margins. They are a combination of alligator and longitudinal cracking patterns that develop near the pavement's shoulder (Wei et al., 2022). The main causes of edge cracks are poor drainage, insufficient lateral support, and heat contraction. The deterioration process is accelerated when moisture infiltrates these fractures, particularly with frequent traffic loading and freeze-thaw cycles (Yan et al., 2024).

If left unrepaired, edge cracks can spread and cause major structural damage, necessitating costly repairs. Several preventative measures should be considered during the design and maintenance stages to avoid edge cracks. These include using temperature-resistant materials that can better withstand thermal changes, enhancing drainage systems to prevent water accumulation, and ensuring that the pavement edge is properly supported by adequate shoulder construction. The spread of deterioration can also be slowed by routine inspection and prompt sealing of small cracks (Zhang et al., 2023). By implementing these strategies, pavement life can be significantly extended and long-term maintenance expenses reduced.

Differential settlement between the pavement and the shoulder is a primary contributing factor to edge cracking (Chai et al., 2023). The shoulder may settle faster than the adjacent pavement if it is made of weaker or non-compacted materials. This vertical offset creates stress concentrations along the pavement edge, leading to the initiation and propagation of cracks.

Figure 3. *Edge cracks: Deterioration (Chai et al., 2023)*

The pavement layers become fatigued over time due to this structural support mismatch, especially when heavier vehicles are subjected to repetitive stress. Seasonal fluctuations also influence the formation of edge fractures; pavement materials expand in hot weather and contract in cold weather (Zou & Amirkhanian, 2021).

Block cracks, as seen in Figure 4, are evident as interconnected rectangular fragments.

Figure 4. *Block cracks Deterioration (Bukhari & Aman, 2023)*

The block cracks, which vary in size from roughly 0.1 m² to 12 m², allow water to leak through. Furthermore, these fractures are frequently observed in pavements with overly dry or aged asphalt mixes containing absorptive particles. They usually arise from the gradual shrinking of the asphalt binder, especially in the presence of temperature changes and extended oxidation. Block cracks, in contrast to fatigue cracking, are a sign of aging and environmental degradation rather than being directly related to traffic loading. Moreover, a suitable asphalt mix design with optimal binder content and good workability is essential for preventing block cracking (Wei et al., 2022). The aging process can be slowed by using anti-oxidation additives and timely surface treatments such as fog seals, rejuvenators, or seal coatings. Routine inspection and preventive maintenance enable early detection of block cracking, allowing quick interventions before serious degradation occurs. To lower the risk of block crack development during construction, it is also critical to ensure proper compaction and to avoid excessively dry mixtures. Inadequate compaction during pavement construction is another cause of block cracking (Bukhari & Aman, 2023).

Fatigue cracks are among the most common and severe forms of distress observed in asphalt pavements. These cracks usually appear due to cyclic tensile strains in the asphalt layer caused by frequent traffic loading. Over time, these forces accumulate, leading to fractures that initiate and spread, particularly in areas with weak pavement structures or inadequate subgrade support. The term "alligator cracking" is often used because this type of cracking typically forms a patterned network of interconnected, sharply angled segments that resemble an alligator's skin (Zhang et al., 2020). These cracks generally occur in areas experiencing high traffic loads, such as wheel paths, and are typically less than 0.3 meters long on their longest side. Fatigue cracks create complex geometries that indicate significant pavement structural failure, as seen in Figure 5.

Figure 5. *Shows Fatigue cracks and Deterioration* ***(****Ahmad & Khawaja, 2018****)***

Moreover, fatigue cracking can be caused by several factors, including moisture, aging of the asphalt binder, insufficient pavement thickness, and poor construction practices. Once initiated, these fractures allow water to seep into the pavement, weakening the base and accelerating disintegration. If not treated promptly, fatigue cracks can develop into potholes, compromising traffic safety and increasing maintenance costs. To reduce the incidence and spread of fatigue-related damage in asphalt pavements, effective design strategies are crucial. These include the use of high-quality materials, appropriate layer thicknesses, and timely maintenance interventions such as crack sealing and surface treatments (Ahmad & Khawaja, 2018).

The strength and longevity of road surfaces are greatly enhanced by the use of advanced materials like polymer-modified asphalt and asphalt concrete, which perform better under environmental stress, heavy loads, and temperature fluctuations. However, high production temperatures can accelerate asphalt aging and reduce its flexibility, which also limits the construction season in cold highland regions. Warm mix asphalt technology is an innovative approach to lowering production temperatures without sacrificing quality or construction efficiency, as clearly explained in Table 1.

Table 1. *Asphalt Pavement Distresses, Causes, & Preventives (Zhao et al., 2023)*

No	Type of Distress	Main Cause	Preventive Measures	Estimated Frequency (%)
1	Fatigue Cracks	Repeated loading and tensile strain in the asphalt layer, structural weakness, and poor subgrade	Proper structural design; increase asphalt thickness; improve subgrade; adequate drainage	30%
2	Potholes	Water infiltration; freeze-thaw cycles; untreated fatigue cracks; severe localized failure	Preventive maintenance, timely crack sealing, and proper drainage	15%
3	Edge Cracks	Lack of lateral support; soft shoulder; poor drainage; heavy edge loading	Reinforce shoulders; improve subgrade; ensure proper side slope	10%
4	Block Cracking	Aging of the binder, thermal contraction, and low flexibility of the asphalt mix	Use modified binders, proper aggregate gradation, and prevent early aging	10%

Literature Review

Extensive studies have unambiguously established that rainfall, climate variability, acidic salts, and surface runoff are the primary drivers of asphalt pavement deterioration. These factors critically accelerate pavement degradation, undermine structural integrity, and ultimately reduce the functional lifespan of asphalt surfaces (Li et al., 2023).

Although previous studies have widely observed erosion effects on asphalt pavements under various environmental circumstances, limited research has focused on erosion-related deterioration within Afghanistan's highway network, particularly along the Kabul–Kandahar corridor. Current literature highlights moisture penetration, inadequate drainage, and temperature-induced stresses as dominant erosion mechanisms; however, their combined influence under Afghanistan's specific climatic and traffic conditions remains insufficiently explored. This research addresses this gap by contextualizing global findings within the operational environment of the Kabul–Kandahar Highway.

Various studies have confirmed that erosion accelerates moisture-related damage and cracking in asphalt pavements, reducing the service life of asphalt surfaces. Several studies have examined the negative effects of erosion on asphalt pavements, demonstrating a direct link between surface water flow and deterioration of road infrastructure. Researchers have investigated a variety of erosion mechanisms and materials, suggesting preventive measures such as modified asphalt mixtures, improved drainage systems, and slope stabilization (Bukhari et al., 2023).

Recent studies have concentrated on increasing the durability of Hot Mix Asphalt (HMA) through material innovations and improved construction techniques. The literature highlights the need for integrated erosion control strategies in road design and maintenance, particularly in areas prone to heavy precipitation and poor soil stability. These findings provide a strong foundation for further investigation into erosion mitigation and pavement preservation practices (Zhou et al., 2021).

Adding fibers or polymers to asphalt binders has shown promise in enhancing resistance to erosion-induced damage and moisture intrusion. Additionally, research indicates that improving compaction efficiency and aggregate gradation enhances the overall durability of asphalt surfaces. Furthermore, performance-based testing and field monitoring have emerged as crucial tools for evaluating the long-term impacts of erosion, enabling more precise forecasts of pavement lifespan and necessary maintenance procedures (Zhou et al., 2021).

Moreover, studies emphasize that erosion effects vary by region, underscoring the importance of adapting pavement design to local topography and climate. For example, freeze-thaw cycles in cold climates worsen erosion by allowing water infiltration and deteriorating the pavement structure, while sand abrasion and wind can cause erosion in arid areas. Therefore, to effectively reduce erosion hazards and improve pavement longevity across various geographic zones, the literature advocates for context-specific design standards, environmental impact assessments, and sustainable construction methods (Zhang et al., 2020).

The word "asphalt" has a long history dating back to ancient languages and societies. Its roots lie in the Akkadian word asphaltu, meaning a rigid, sticky material. It was known as asphaltos in Homeric Greek, which means "to make safe" or "to stabilize." Over the centuries, this term changed from "asphaltum" in Latin to "asphalt" in modern English (Asphalt Institute, 2007). Asphalt has been used for thousands of years as a natural and practical substance. Natural bitumen was used by ancient Mesopotamian and Near Eastern societies for waterproofing buildings, sealing vessels, and even in early building methods, according to archeological data. Trinidad's Pitch Lake, a significant bitumen reservoir to this day, is one of the best-known natural asphalt sources (Gao et al., 2022).

The mid-19th century marked a critical turning point in the modern evolution of asphalt. The first bituminous road surface was built in Paris, France, in the 1850s. Natural rock that had been wet with asphalt, ground into a powder, and then solidified with hot iron tools made up this pavement. This signaled the start of asphalt's widespread use in road construction and civil engineering.

As the petrochemical industries developed during the 20th century, refined or synthetic asphalt made from crude oil was produced. Better quality control, mass production, and broader use of asphalt in infrastructure projects were made possible by this advancement. In addition to roads, asphalt is now used for bridge decking, airport runways, roofing systems, and even in specialty industries such as textiles and pharmaceuticals. To sum up, asphalt has evolved from a naturally occurring bonding agent to a forward-looking material essential to contemporary infrastructure. It is a material with a rich history and a complex future influenced by industrial demand and innovation (Almeida & Picado-Santos, 2022).

Figure 6. *Asphalt with good skid resistance (Wang et al., 2024)*

The term "asphalt film" refers to a thin layer of bituminous material typically applied during road construction. While it is not a structural layer like the base or surface course, it is crucial to the pavement system's performance and longevity because it serves as a protective barrier and bonding agent between pavement layers. Though one of the main functions of asphalt film is to ensure proper adhesion between layers, particularly between the base course and the asphalt surface layer, the lack of this bonding layer can result in premature pavement failures due to slippage or delamination under traffic loads (Wang et al., 2024).

The asphalt film also helps distribute stresses more evenly by preventing structural separation. Moreover, asphalt film serves as a moisture barrier, preventing water from seeping into the lower pavement layers. This is especially crucial in regions where excessive rainfall or freeze-thaw cycles can cause potholes, rutting, fatigue, and subgrade weakness. The asphalt film's waterproofing enhances the road's overall durability (Long et al 2023).

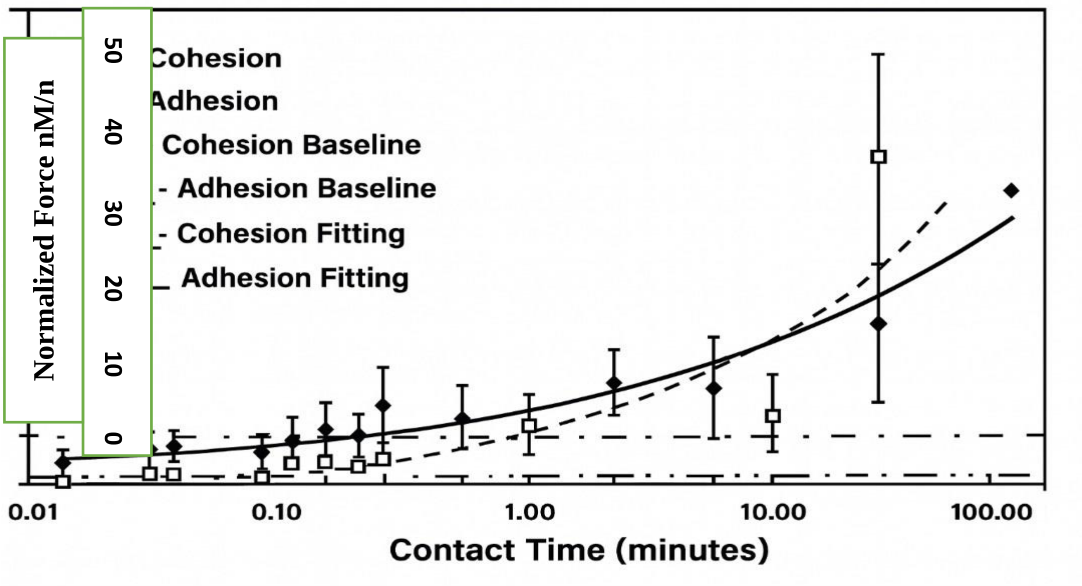

Figure 7. *Adhesive & Cohesive bonding (Nie et al., 2023).*

Methods and Materials

This research adopted a mixed-methods approach, integrating both quantitative and qualitative data to examine the impact of erosion on asphalt pavement along the Kabul–Kandahar highway. The study utilized field surveys, structured questionnaires, and expert interviews to collect reliable perceptions. These methods provided a comprehensive understanding of the causes, consequences, and potential moderation strategies for asphalt pavement erosion. The study was conducted along the initial 12-kilometer segment of the Kabul–Kandahar highway, starting from the southern outskirts of Kabul city. This portion of the road represents a critical transition zone where urban infrastructure meets the early stretches of interprovincial transportation routes. The selected section was chosen due to its exposure to frequent traffic loads, seasonal rainfall, and visible signs of erosion-related pavement distress. This area also enabled field observation and data collection from nearby governmental institutions involved in road maintenance and planning. In this research article, both qualitative and quantitative approaches were employed. The quantitative component was derived from the questionnaire, in which respondents provided numerical evaluations expressed as percentages ranging from 0 to 100. The qualitative component involved categorical assessments designed to determine the degree of performance or condition, using descriptors such as "poor," "good," "better," "perfect," "excellent," and similar evaluative terms. While questionnaires and practice interviews were employed to support understanding, the main emphasis of this study is on technical field observations, pavement condition valuation, and material-related evaluations. Survey-based inputs were therefore used as additional indications to reinforce the scientific explanation rather than as the principal analytical foundation.

In addition to its technical and environmental characteristics, the Kabul–Kandahar highway is not only one of the most vital domestic transportation corridors but also plays a strategic role in connecting Afghanistan to regional and international transit networks. This highway is part of the North–South transit corridor, linking key cities across the country to southern ports and international borders. Considering its economic role in the transport of goods and passengers, and in facilitating access between rural and urban areas, the maintenance and enhancement of this corridor are regarded as essential priorities within national development policies and regional cooperation frameworks. Given the climatic conditions, heavy traffic loads, and insufficient drainage and long-term monitoring systems, this segment remains structurally vulnerable. There is a critical need to implement modern technical supervision mechanisms, utilize durable construction materials, and align road design and maintenance practices with international standards. Furthermore, establishing well-equipped monitoring and operational units at strategic intervals could significantly improve traffic management, enable timely responses to structural damage, and extend the functional lifespan of the pavement along this vital stretch of the highway.

Climatic Circumstances

The climatic circumstances at the initial segment of the Kabul–Kandahar highway, located on the southern outskirts of Kabul, are characterized by a semi-arid continental climate. This region experiences significant seasonal temperature variations, with hot, dry summers when temperatures may exceed 35°C and cold winters that occasionally bring sub-zero temperatures and limited snowfall. Rainfall is mainly confined to spring and autumn, with an average annual precipitation of approximately 300–400 mm. Although snowfall is not abundant, it can still affect traffic and road surface conditions during peak winter. Wind patterns are generally moderate, but dust-laden winds from surrounding barren areas may exacerbate surface erosion and reduce visibility, particularly in late summer. The combination of seasonal precipitation, freeze-thaw cycles, and sporadic flash floods contributes to pavement wear and structural vulnerability, making climate-responsive design and maintenance essential for this portion of the highway (Lu et al., 2023).

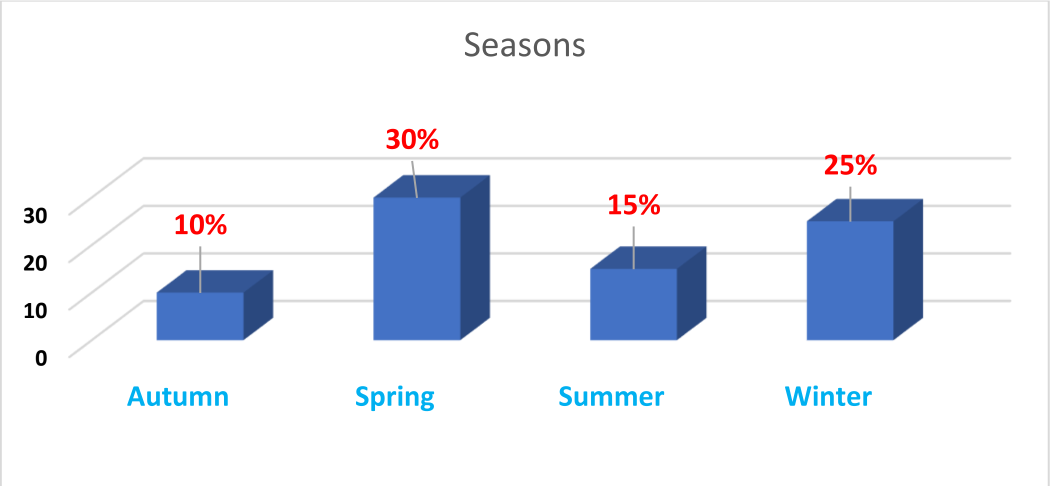

Figure 8. *Climatic Condition of precipitation (Lu et al., 2023)*

Data Collection

Primary data were collected through both physical (on-site) surveys and online questionnaires. The main data sources included key government departments involved in road design, maintenance, and public infrastructure. Specifically, data were obtained from:

- Directorate of Road Maintenance and Preservation
- Directorate of Survey and Design
- Engineering Directorate of the Ministry of Public Works

Participants in the survey included engineers, technical staff, administrative personnel, and other stakeholders involved in road infrastructure planning and maintenance. Quantitative data were collected through structured questionnaires that assessed erosion severity, pavement condition, and contributing environmental and structural factors. Qualitative insights were collected through interviews and open-ended responses to understand respondents' practical experiences and expert opinions.

Asphalt Mixing

A combination of Bitumen, mineral filler, and coarse and fine particles was used throughout the mixing process to create asphalt mixtures. To guarantee that the finer particles were evenly distributed throughout the mixture, the aggregates and filler were first dry-mixed. The mixture was then supplemented with heated bitumen. A regulated temperature of roughly 145 ± 5°C was used for the mixing procedure, which is ideal for fully covering the aggregates and ensuring uniform mixing.

Data Analysis

For this research, data analysis was carried out using Google Forms, based on a set of 22 specialized questions administered to highly experienced, professionally qualified engineers. The thorough mixing process below is essential for producing high-quality asphalt with adequate workability, durability, and mechanical performance suitable for road pavement construction. The entire mixing operation was carried out in accordance with BS EN 12697-35:2004 standards (British Standards Institution, 2004) to maintain stability and quality. The mixing duration and speed were adjusted based on the mixture's viscosity and aggregate characteristics, ensuring that all components were uniformly distributed without separation or excessive oxidation of the binder.

Figure 9. *Mixing of asphalt materials (Lu et al., 2023)*

Findings

In this section, a systematic data collection effort was carried out using both online and offline survey methods to assess the effects of erosion on asphalt pavements, specifically along the Kabul–Kandahar Highway. A comprehensive survey with 28 targeted questions was developed using Google Forms and distributed in both digital and hard-copy formats to 103 expert civil and construction engineers. Participants included professionals from Kabul Municipality, the Ministry of Public Works, the Ministry of Urban Development, and master's students specializing in road construction engineering. The participants were selected based on their professional involvement and hands-on experience in road design, construction, and maintenance.

The questionnaire was thoughtfully designed to gather information on various erosion-related factors impacting asphalt pavements, including environmental exposure, material longevity, structural deterioration, and the frequency and types of erosion observed in the field. Respondents were asked to assess the condition of pavement components and identify trends in erosion-related degradation across different road segments. Both their quantitative and qualitative responses provided valuable, experience-based insights that helped to identify real-world challenges and potential solutions in asphalt pavement maintenance.

The survey's main findings indicated general agreement among respondents that the material properties and composition of the asphalt pavement along the Kabul–Kandahar Highway are appropriate for the region's operational and environmental conditions. While highlighting the suitability of current material choices, the range of expert responses also identified specific erosion vulnerabilities, particularly in high-risk areas. The detailed responses reflect both individual technical expertise and real-world field experience gained through years of direct engagement with Afghanistan's road infrastructure.

The data collected via Google Forms was processed using MS Excel for in-depth descriptive and logical statistical analysis, as presented in the next section.

As shown in Figure 9, responses from 102 professional participants on their familiarity with the concept of asphalt pavement erosion were analyzed. A substantial majority (81.4%) reported familiarity with asphalt pavement erosion, indicating strong awareness among professionals and stakeholders. In contrast, only 18.6% of participants indicated no knowledge of asphalt pavement erosion. These findings suggest that awareness of this issue is relatively high within the surveyed group, which is a positive indicator for future initiatives related to road infrastructure maintenance and erosion prevention strategies. The high level of familiarity may also reflect the growing emphasis on pavement sustainability and the increasing importance of erosion-related challenges in the road construction and civil engineering sectors.

Experiential deterioration patterns along the Kabul–Kandahar Highway demonstrate a strong association between erosion severity and asphalt pavement distress. Field evidence indicates that erosion accelerates moisture diffusion, compromises interlayer bonding, and promotes surface cracking, which, in turn, evolves into potholing and structural degradation. These findings align with established pavement performance theories and confirm erosion as a critical factor influencing asphalt durability along this highway segment.

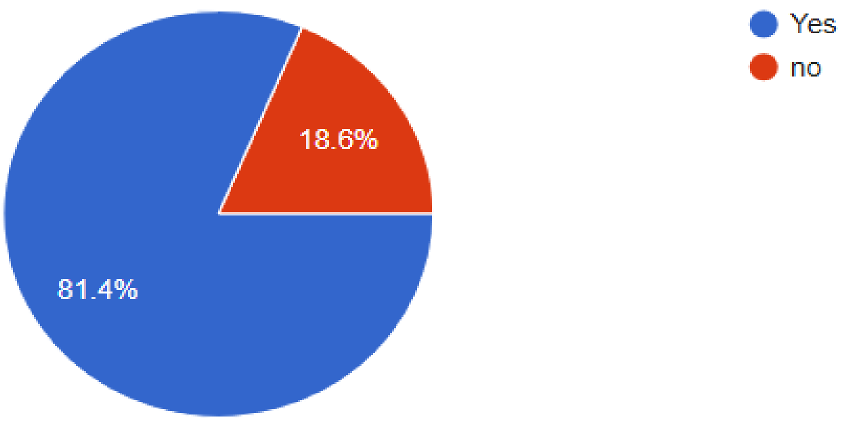

Figure 10. *Familiarity with the concept of Asphalt Pavements Erosion*

As shown in Figure 11 below, responses from 101 expert participants on whether erosion significantly affects the durability of asphalt pavements were analyzed. A substantial portion of the respondents (52%) answered "Yes," indicating strong agreement among professionals that erosion plays a critical role in pavement deterioration. In contrast, a small minority (5%)

responded "No," denying any significant impact. Additionally, 20.6% (21 participants) chose "Maybe," reflecting a degree of uncertainty or a call for further investigation. Meanwhile, 23.5% (24 participants) answered "Sometimes," suggesting that erosion's influence may depend on specific conditions or contexts. These results indicate that while a majority of experts acknowledge erosion as a key factor affecting asphalt pavement durability, a considerable portion of respondents either qualify their agreement or express reservations. This diversity of opinion highlights the complexity of the issue and underscores the need for ongoing research and nuanced approaches in pavement maintenance and erosion mitigation strategies.

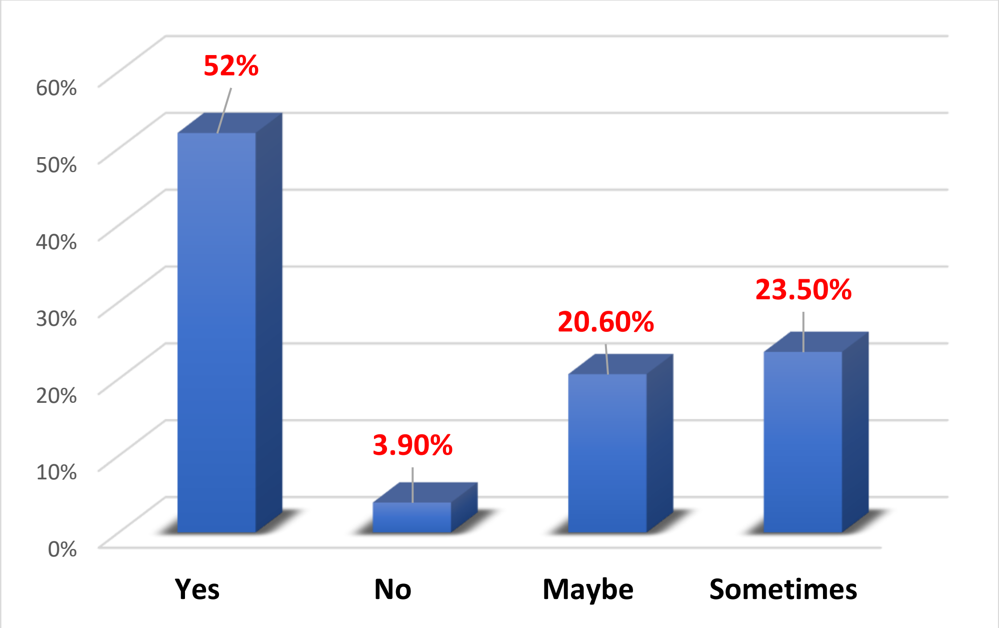

Figure 11: *Does erosion significantly affect the durability of asphalt pavements?*

Figure 12 presents the professional assessment of 102 experienced engineers and infrastructure specialists on the current stage of erosion-related deterioration of the Kabul–Kandahar highway, one of Afghanistan's most vital national corridors.

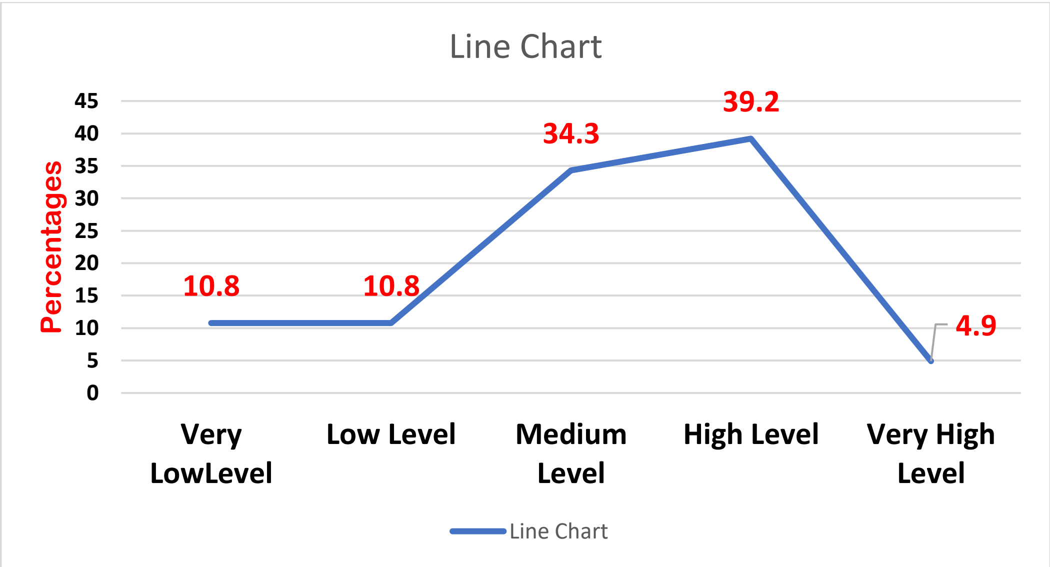

Figure 12. *Deterioration stage of Erosion on Kabul-Kandahar Road*

The responses show clear concern among professionals: about 40 expert engineers (39.2% of respondents) selected "high level deterioration," indicating that erosion damage is already extensive and is seriously compromising the road's structural soundness and usability. This result demonstrates the critical need for corrective and preventive measures. An additional 34.3% of respondents reported a "medium level" of degradation, indicating that while the damage is not currently catastrophic, it is developing and could worsen rapidly without prompt reinforcement and maintenance. Approximately 10.8% of respondents (roughly 11 professionals) selected "low" or "very low" levels, suggesting that only a small percentage of road segments may still be in relatively stable condition or have recently undergone rehabilitation.

A smaller group (4.9%, or about 5 individuals) classified the erosion deterioration as "very high level," likely representing severely damaged areas that are either near failure or already nonfunctional. According to the distribution of responses, more than 70% of experts believe that the Kabul–Kandahar Road is experiencing medium to high, or very high, erosion. This is concerning for a national roadway that connects important population and economic centers. The range of deterioration levels also reflects variations in drainage capacity, environmental exposure, construction quality, and ongoing maintenance across different segments of the route. Furthermore, most professional engineers consider erosion deterioration along the Kabul–Kandahar Road to be at medium to high levels, indicating a national infrastructure risk that requires strategic action.

As demonstrated in Figure (13), according to the responses of (102) asphalt specialists, the main causes of asphalt pavement erosion in Afghanistan are heavy vehicle traffic (reported by (56) respondents or (54.9 %), inadequate water drainage systems (52 respondents or (51 %), and lack of regular maintenance (50 respondents or (49 %).

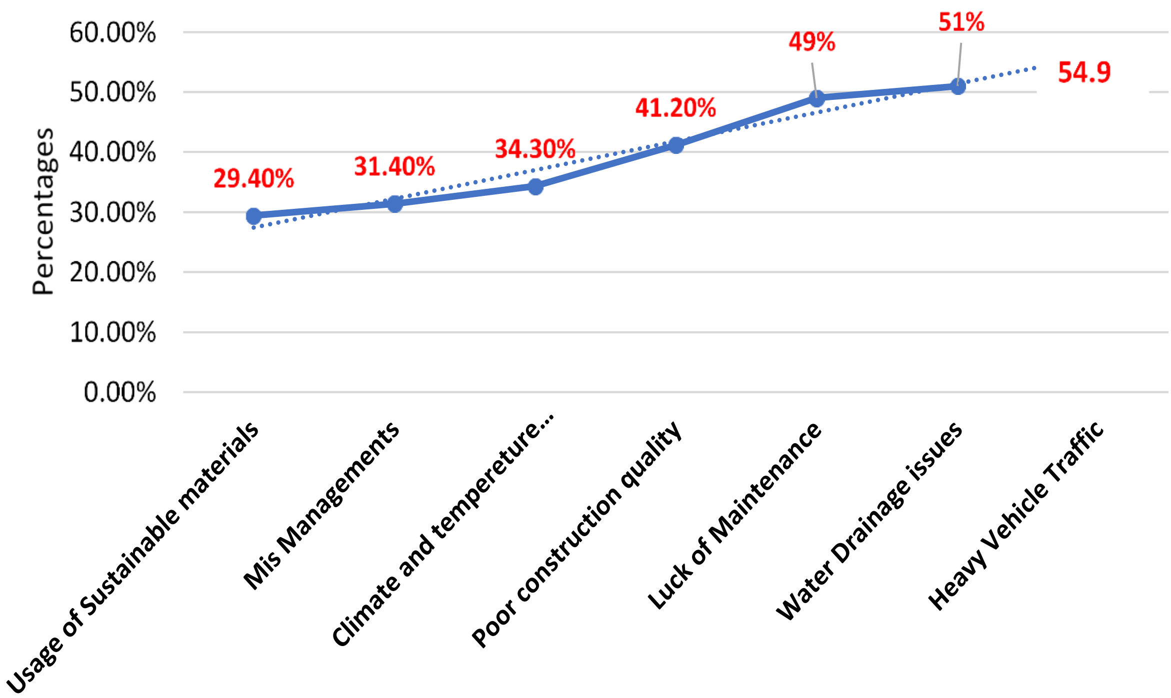

Figure 13. *The main causes of asphalt pavement erosion on the Kabul-Kandahar Highway*

Additional contributing factors include poor construction quality (41.2%, 42 respondents), climate and temperature fluctuation (34.3%, 35 respondents), corruption and mismanagement (31.4%, 32 respondents), and the use of substandard materials (29.4%, 30 respondents). Only (18.6 % 19) respondents) mentioned other minor causes.

These findings suggest that overlapping technical issues and governance flaws are the cause of road degradation in Afghanistan. Coordination is necessary for a lasting solution, which includes severe quality control in construction, anti-corruption measures, structured maintenance programs, better drainage designs, and limitations on high traffic. The resilience of the country's road system would continue to be jeopardized in the absence of thorough change in these areas.

Responses from 103 experienced participants about the best strategies to prevent asphalt erosion from affecting pavement are shown in Figure 14. Of the respondents, 28.3% highlighted the significance of timely maintenance, while 29.3% emphasized the use of high-quality materials as the most important factor. Additionally, 18.2% cited the importance of improved maintenance procedures, and 22.2% believed that using high-quality asphalt mixtures could greatly reduce erosion. A small percentage, 2%, recommended different techniques under the category of "Others."

These results indicate that a significant proportion of experts identified the use of high-quality materials and timely maintenance as the best approaches, even though various strategies are considered beneficial. To effectively reduce the effects of erosion on asphalt pavements, greater attention and implementation should be focused on enhancing material quality and ensuring timely maintenance, as these two approaches were prioritized by the majority of experts.

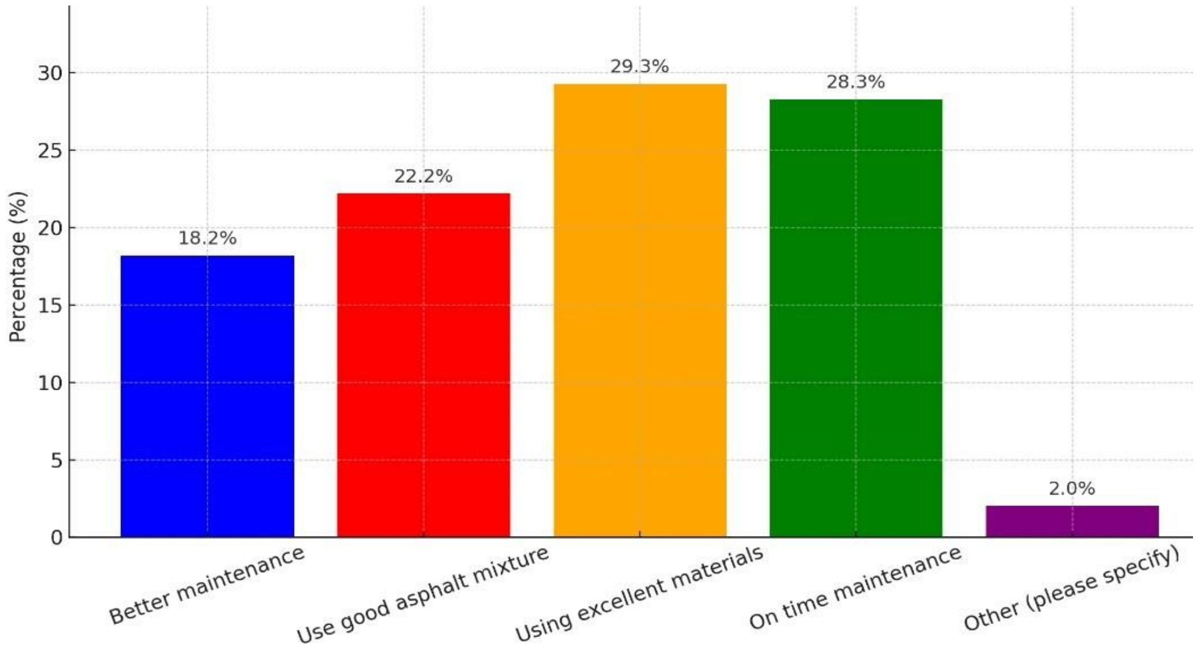

Figure 14: *Ways to prevent asphalt erosion impact on pavements*

Discussion

This research emphasizes the Kabul–Kandahar highway, an essential logistical and economic road in Afghanistan, though this study investigated the effects of erosion on asphalt pavement. The results, which were derived from the answers of (103) experienced infrastructure professionals, provide profound insights into the perceptions of asphalt erosion, as well as its visible signs, contributory reasons, and institutional duties for road maintenance. One of the main findings was that surface-level indicators were more common, with 61.8% of respondents citing road cracking as the leading erosion indicator. This result is consistent with global research, which frequently views surface cracking as the first sign of more serious structural degradation (Wang et al., 2020; AASHTO standards). Furthermore, 42.2% and 47.1% of respondents, respectively, reported general road deterioration and road decay, supporting the notion that erosion is a multi-layered, progressive process rather than a single event. These findings are consistent with related research carried out in areas with inadequate drainage systems, where surface runoff and culvert deficiencies accelerate asphalt deterioration.

Furthermore, professionals' concerns about the current state of road deterioration are also evident from the discussion: (39.2 %) of respondents indicated significant erosion-related damage. Moreover, field reports highlighting obvious structural defects along the mentioned area highways are consistent with this impression. Afghanistan appears to have additional difficulties, such as inadequate institutional coordination and financial limitations, compared to comparable studies conducted in South Asia and the Middle East, where high vehicle loads, severe weather, and subpar construction techniques are frequent causes of road failure. The function of institutional structure and governance is another important finding. The Municipality was cited by a significant (39.2 %) of experts as the primary agency in charge, followed by the Ministry of Urban Development (31.4 %). However, inadequate maintenance cycles and inactive erosion response have been caused by a lack of transparency and responsibility destruction. The broader development literature has rebounded these institutional problems, arguing that technical interventions need to be combined with improved inter-agency coordination and policy reform (UNESCAP, 2019).

The study also revealed a concerning deficiency in protective infrastructure: only 12.8% of respondents thought that the current culvert and drainage systems adequately protected roads. This supports the claim that inadequate water management is one of the main causes of erosion. According to comparative research conducted in Iran and Pakistan, inadequate drainage systems rank among the leading causes of pavement failure (Khan et al., 2021). Notably, the results highlight the absence of uniform standards; however, 49% of experts refer to worldwide standards (such as AASHTO), and 21.6% said they do not use any standard procedures at all.

Conclusion

The study identified the main causes and consequences of asphalt pavement erosion on the Kabul–Kandahar Highway. Furthermore, pavement deterioration is accelerated by environmental factors such as dust storms, freeze–thaw cycles, rainfall, and heavy traffic loads. The principal distress types observed include fatigue cracking, potholes, rutting, edge cracking, and surface erosion. Survey data showed increases in cracks, potholes, delays, accidents, and user dissatisfaction compared to previous years. The study highlights the urgent need for quick reforms and stronger institutional capacity in road maintenance. Flexible pavements require climate-resilient materials, adequate drainage, and durable construction practices. The use of high-quality asphalt coatings, monitoring sensors, and proactive maintenance can significantly reduce erosion.

The study's findings are limited by seasonal data gaps, which reduce accuracy. Future research should apply long-term, multi-season monitoring to ensure more reliable results. The findings are expected to support politicians, engineers, and stakeholders in civilizing road stability and improving organizational investments. They can also guide policymakers in accepting maintainable road management approaches. However, the engineers may utilize the results to design more durable asphalt pavement structures. Moreover, stakeholders can allocate resources effectively to minimize erosion. Though to prioritize methodical maintenance and context-specific erosion-control measures, backed by institutional support, to reduce premature pavement failure and improve corridor safety.

Overall, the study approves that erosion plays a pivotal role in accelerating asphalt pavement deterioration on the Kabul–Kandahar Highway. Addressing erosion through scientifically informed material selection, drainage development, and climate-resilient pavement design is important to ensure the long-term performance and safety of this strategic transportation strip.

Suggestions for Future Research

1. Assess the Long-Term Performance of Polymer-Modified Asphalts in Afghanistan's Climate:
   Upcoming education must focus on evaluating the effectiveness of SBS- and epoxy-modified asphalt mixtures under Afghanistan's extreme temperature fluctuations, heavy traffic volumes, and freezing-liquefaction events.
2. Evaluate the Effectiveness of the Locally Sourced Materials and Additives:
   Researchers are encouraged to conduct both laboratory and field studies to assess the durability and compatibility of locally available aggregates, fillers, and anti-stripping agents in Afghan environmental conditions.
3. Develop Regional Erosion Risk Maps and Drainage Models:
   Future research should aim to develop erosion-vulnerability maps and drainage designs tailored to Afghanistan's diverse topography, rainfall patterns, and soil types. These tools can support erosion prevention and optimize road design.

Authors Contributions

- Barialai Mohammadi was responsible for the conception, design, and writing of the research paper, including gathering data, conducting a literature review, and drafting the manuscript.
- Abdulhai Kaiwaan and Imran Safi judgmentally reviewed the script, provided substantial feedback, and contributed to revisions that improved the quality and clarity of the final paper.
- All authors reviewed and approved the final version.

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