Failure and Maintenance of Flexible Pavement: A Case Study of Mahendranagar City Roads, Nepal

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Abstract

Sustainable urban mobility hinges on the structural integrity and serviceability of road infrastructure, particularly in developing regions like Nepal, where flexible pavements dominate the arterial network. This study systematically evaluates the failure mechanisms of flexible pavements across six critical urban road segments: Streets 1 to 5 and the Hospital Line of Mahendranagar City, through field inspections guided by ASTM D6433-20 standards. The primary objective was to classify distress types, determine causative factors, and recommend context-appropriate maintenance interventions. The assessment revealed a disproportionately high prevalence of potholes and edge failures, attributed to inadequate drainage, substandard construction practices, and prolonged neglect of routine maintenance. Only Street 1, recently constructed, exhibited no failures. The findings underscore an urgent need for strategic pavement rehabilitation, drainage optimization, and the implementation of a localized pavement management system to ensure long-term performance, user safety, and cost-effective infrastructure sustainability.

Keywords: Flexible Pavement, Arterial Network, Distress, Routine Maintenance, Mahendranagar

Introduction

Transportation infrastructure serves as a cornerstone of national development, shaping both economic and social trajectories. Among various transport modes, road networks remain the primary medium for moving goods and people, especially in developing countries like Nepal. A well-developed and efficiently maintained road network enhances connectivity, reduces travel time, promotes regional integration, and fosters economic prosperity (Pokharel, Bertolini, and Te Brömmelstroet 2023). For a country like Nepal, where geographical diversity poses significant transportation challenges, road infrastructure plays an especially critical role in regional development.

Flexible pavements, composed of layered structures that distribute traffic loads over the subgrade, constitute the majority of roads in Nepal, including Mahendranagar, a growing urban hub in the far-western Terai region. These pavements are favored for their initial lower construction costs, shorter construction periods, and the flexibility to adapt to moderate subgrade deformations. The pavement deterioration process begins very slowly, making it possibly undetectable, and then accelerates at faster rates over time (Shakya et al. 2025). Pavement surface deformation can result in premature breakdown, which affects ride quality and safety. Road users and road authorities are concerned about the potential for flexible pavement to deteriorate, which is prevalent in many developing nations (Degu et al. 2022). Also, flexible pavements are also more prone to a variety of structural and functional distresses, such as cracking, rutting, potholes, and surface deformation (R. 2024). These failures are influenced by multiple factors including high traffic volume, overloading of vehicles, poor drainage conditions, temperature-induced aging of bitumen, and inadequate construction practices (Irokwe, Nwaogazie, and Sule 2022). Flexible pavements are susceptible to various types of failures, including alligator cracking, shear-induced and longitudinal cracking, frost heaving, inadequate bonding between layers, reflective cracking, corrugations, bleeding, pumping, depressions, potholes, segregation, and consolidation of pavement layers (Sharma, Boora, and Kumar 2025).

Mahendranagar has experienced a considerable rise in vehicular traffic, especially in its market areas and along arterial roads, due to the concentration of commercial activities, shops, and daily markets. These zones attract a high volume of mixed traffic, including motorcycles, auto-rickshaws, and light delivery vehicles, which subjects the pavement to frequent stop-and-go movement, surface abrasion, and localized overloading. Such traffic patterns contribute to the accelerated wear of flexible pavements, leading to surface distress such as raveling, cracking, and rutting, particularly where pedestrian and vehicular interactions are dense and drainage infrastructure is insufficient (Nantung et al. 2021). Furthermore, the region experiences high summer temperatures, often exceeding 40°C, which can significantly reduce the stiffness of bituminous binders, leading to bleeding, rutting, and thermal cracking. These climate-related factors exacerbate pavement vulnerability, particularly when coupled with poor drainage and substandard materials (Amirthu Rikaa S, Karthikaa M, and Eunice J 2024). Inadequate drainage is another critical factor contributing to pavement deterioration, as prolonged water infiltration weakens the subgrade and base layers, reducing load-bearing capacity and accelerating structural failures such as potholes and cracking (Garoma Wayessa 2019).

Roadway distresses in Mahendranagar are further intensified by the lack of systematic maintenance and insufficient investment in preventive repair. Many flexible pavements in the city exhibit early signs of failure within a few years of construction, reflecting deeper systemic issues in design, materials, and construction supervision. Common defects observed include longitudinal and alligator cracks, surface undulations, edge breakups, and localized subsidence, each traceable to specific technical causes such as subgrade failure, inadequate compaction, insufficient bitumen content, or clogged drainage systems. The deterioration of these roads not only hampers traffic flow but also contributes to vehicular damage, and road safety concerns (Tahir, Tabassum, and Rahim 2023).

The Pavement Condition Index (PCI), a standardized visual rating system developed by the U.S. Army Corps of Engineers, and the Present Serviceability Index (PSI), which assesses ride quality, are widely used globally to assess pavement performance and guide maintenance planning (Isradi et al. 2023). These evaluation frameworks offer reliable tools for diagnosing the severity and extent of failures, which can inform data-driven rehabilitation and maintenance strategies. In Nepal, however, the application of such frameworks is still in a nascent stage, and localized adaptation is essential to address region-specific conditions.

A proper understanding of failure mechanisms is vital for formulating effective maintenance strategies. Failures in flexible pavements generally stem from fatigue under repeated loading, shear failure in base and sub-base layers, or water-induced weakening of the subgrade. These modes of failure, if not addressed timely, progress into more severe distresses that require extensive rehabilitation, which is economically burdensome. Hence, the role of timely and appropriate maintenance, including patch repair, resurfacing, and periodic overlays, is crucial to sustaining pavement life and performance (Inyang et al. 2024). Moreover, the lack of skilled technical personnel, inadequate funding, and poor-quality control during construction further complicate the pavement management process (Zhao et al. 2024). Adopting timely and context-specific maintenance techniques is essential to extend pavement lifespan and minimize long-term rehabilitation costs.

Objectives

- To assess the condition and failure patterns of flexible pavements in the Mahendranagar City Roads (Arterial Networks).
- To recommend evidence-based maintenance and improvement strategies for flexible pavements.

Significance of study

This study is about the Identification of Defects and Maintenance of arterial road networks of Mahendranagar City Road, Nepal. By visiting the location and conducting a comprehensive inspection, the most common forms of cracks and defects on Mahendranagar City Road will be taken into consideration for this study. Maintaining flexible pavements for user safety and the city's visual appeal presents the largest problem. The road deteriorates with time due to the amount and variety of vehicle types moving. It may result in mishaps, which might result in property damage and fatalities if not properly maintained. Therefore, it has to be properly maintained regularly at some point in time. The state of the City's roads is the responsibility of the Department of Roads, the Department of Urban Development, and the Municipality. This study helps the municipality understand the types and locations of failures as well as the type and technique of maintenance required to address these failures to maintain road safety.

Literature Review

The performance of flexible pavements under varying traffic and environmental conditions has been a central focus of transportation engineering research for decades. Flexible pavements, due to their layered structure and bituminous composition, are prone to distress mechanisms such as rutting, fatigue cracking, potholes, and surface deformation, particularly in regions with high traffic loads and climatic extremes. A robust literature base exists that addresses both the causative mechanisms and the remedial frameworks for pavement distress. Mechanistic-empirical (M-E) models have advanced the predictive capability for pavement distress by incorporating traffic load spectra, climatic data, and material behavior. (Gupta, Kumar, and Rastogi 2014) developed an M-E based prediction model that correlates environmental factors and axle loading to fatigue cracking and rutting in flexible pavements. Their research demonstrated the need for region-specific calibration of these models to account for local variations in climate and subgrade strength.

Globally, various studies have assessed flexible pavement failure mechanisms under different environmental and loading scenarios. (Wang et al. 2024) observed that inadequate drainage and vehicle overloading were primary contributors to pavement deterioration in urban regions, mirroring the issues faced in Mahendranagar. (Bekele and Tantu 2022) highlighted the significance of traffic composition and improper maintenance schedules in accelerating surface distress in urban roads. Balancing environmental sustainability and economic feasibility is essential in developing countries like Nepal. (Demir et al. 2023) introduced a multi-objective optimization framework that considers both carbon emissions and lifecycle costs in flexible pavement design. Their approach provides a sustainable decision-making model particularly relevant in resource-constrained contexts. Applying such a model in Nepal could guide the selection of eco-friendly materials and promote sustainable rehabilitation practices while reducing long-term costs.

While understanding the causes of failure is critical, it is equally important to assess the effectiveness of maintenance and rehabilitation strategies. (Lee, Wilson, and Hassan 2017) evaluated multiple flexible pavement rehabilitation methods, concluding that strategy selection should be based on lifecycle cost analysis and distress severity. The inclusion of patch repair, resurfacing, and base reconstruction in response to distress types was shown to significantly extend pavement life. These strategies should be adopted in Mahendranagar where frequent failures occur but rehabilitation efforts are often reactive rather than preventive. Existing studies predominantly focus on national highways or large-scale expressways, while few address the failures of urban pavements in small cities. Furthermore, limited research in Nepal incorporates sustainability frameworks in pavement maintenance planning.

Materials and Methods

Site Selection

The study area comprises a significant portion of the Bhimdatta Municipality in the Kanchanpur district as shown in Figure 1, which incorporates street numbers 1-5 and the free line of the city center of Mahendranagar City. The total length of 2460 meters, with each street having 410 meters, was taken for research.

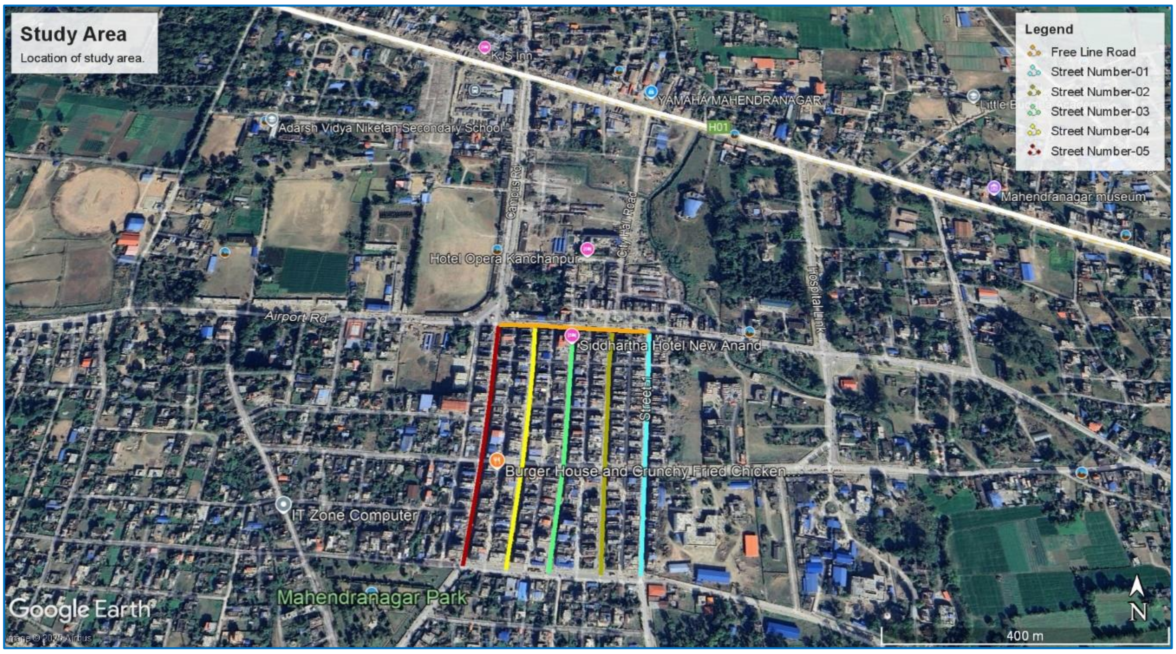


Figure 1: Study Area

Data Collection, Classification and Analysis

The data was collected using a quantitative approach through field measurements and visual inspections. To ensure systematic and standardized data collection on pavement surface distresses, the study adopted the guidelines outlined in ASTM D6433-20, *Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys* (ASTMD6433 n.d.). A week-long field survey and measurement study was conducted to assess pavement failures and deterioration along five streets in Mahendranagar Bazar and the Hospital Road. The visual assessment data for each road segment was organized into tables, and based on this, the percentage of pavement defects across different sections was calculated and illustrated graphically. Based on the severity and type of failures identified, appropriate maintenance strategies were proposed considering their suitability for each specific condition.

Results and Discussion

According to the assessment survey's findings, the Mahendranagar City area experiences a variety of pavement deteriorations and failures. Each street is evaluated separately, as streets 2,3,4,5, and freeline (hospital road) were existing parts, and street 1 was newly constructed.

Street Number:1

The road of Street no. 1 has been freshly constructed. Therefore, no failure of any kind was found there.

Street Number:2

This section includes the majority of pavement failure types. The types of the failures with their percentages in street 2 are listed below:

- **Edge Failure (23%)**: Most common distress, likely caused by poor shoulder support and drainage issues; requires edge strengthening and sealing.
- **Cracking (22%)**: Indicates fatigue and thermal cracking due to high temperatures and load repetition; suggests need for crack sealing and overlays.
- **Potholes (22%)**: Result from prolonged water infiltration and neglected cracks; demand full-depth patching and drainage improvement.
- **Wear and Tear (22%)**: Common in busy market zones with frequent braking; surface treatment like slurry sealing is needed.
- **Segregation (11%)**: Points to construction quality issues; necessitates localized resurfacing and stricter material control.

Table 1: Frequency of defects in Street no.2

Type of Failure	Frequency
Edge Failure	2
Patching	0
Segregation	1
Pothole	2
Cracking	2
Wear and tear	2
Total	**9**

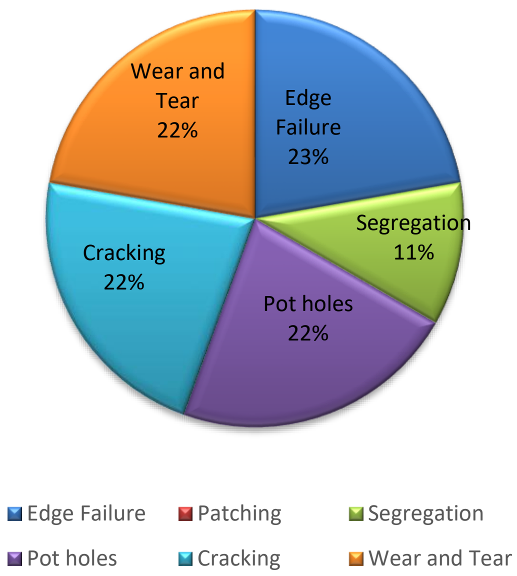


Figure 2: Percentage of defects in Street no. 2

The data indicates a uniformly high presence of structural and surface-level distresses, reflecting both aging infrastructure and environmental as well as traffic-related stressors.

Street Number 3

The pavement failure distribution of Street No 3 is as below:

- **Pothole (55%)**: Dominant failure type, likely caused by water infiltration, weak subgrade, and inadequate patching. Urgent full-depth patch repair and improved drainage systems are needed to prevent further degradation.
- **Edge Failure (36%)**: Signifies insufficient lateral support, possibly due to shoulder erosion or overloaded traffic near pavement edges; requires edge stabilization and sealing measures.
- **Segregation (9%)**: Indicates improper material mixing or laying techniques during construction; calls for localized resurfacing and better construction quality control

Table 2: Frequency of defects in Street no.3

Type of Failure	Frequency
Edge Failure	4
Segregation	1
Pothole	6
Total	**11**

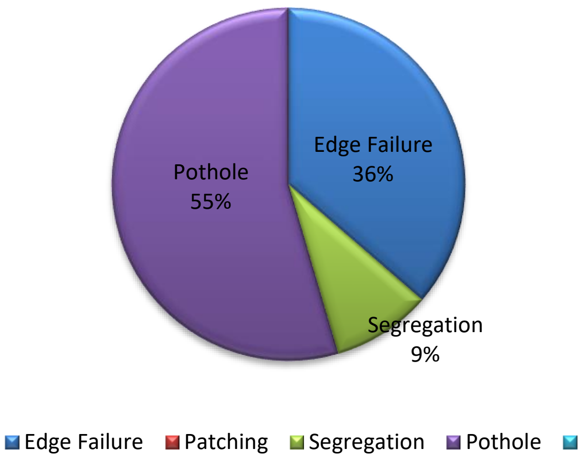


Figure 3: Percentage of defects in Street no. 3

This failure pattern on Street 3 reflects a critical need for prioritized pothole rehabilitation, structural reinforcement of edges, and strict quality assurance to maintain road usability and safety.

Street Number 4

Street number 4 features the following pavement failure severity:

Table 3: Frequency of defects in Street no.4

Type of Failure	Percentage	Description
Pothole	83%	This is the most severe and dominant failure on Street No. 4. Potholes pose serious risks to vehicle safety, increase maintenance costs, and are clear signs of structural deterioration in the pavement.

Edge Failure	6%	These are likely caused by poor drainage or lack of support at the pavement edges. Though not widespread, they can lead to further damage if left untreated.
Patching	6%	Indicates previous repair work. Frequent patching might suggest ongoing or recurring pavement issues that haven't been properly addressed.
Segregation	5%	A relatively minor portion. Segregation often results in weak spots in the pavement, potentially leading to future potholes or surface deterioration.

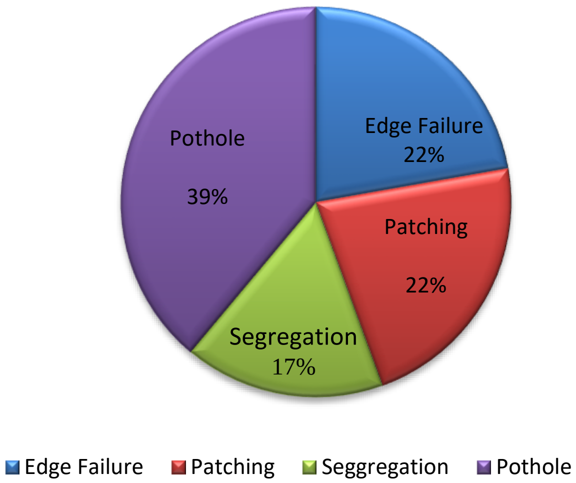
Street Number 5

A significant extent of structural distress and surface deterioration is evident along both the longitudinal and areal dimensions of Street No. 5. The classification and proportional representation of pavement failure types are as follows:

- **Segregation (17%)**: Approximately 17% of the roadway exhibits material segregation, indicating a non-uniform distribution of bituminous constituents, which compromises the homogeneity and performance of the surface course.
- **Potholing (39%)**: Nearly 39% of the pavement area is affected by potholes, representing severe localized disintegration of the wearing surface due to loss of cohesion and subgrade instability.
- **Patching and Rutting (22%)**: About 22% of the pavement demonstrates distress from surface rutting, patching interventions, and progressive surface wear, indicative of repetitive loading and insufficient structural integrity.
- **Edge Failure (22%)**: Edge-related distress accounts for 22% of the total roadway section, attributed to inadequate lateral support, poor drainage, and traffic loading beyond design limits.

Table 4: Frequency of defects in Street no.5

Type of Failure	Frequency
Edge Failure	4
Patching	4
Segregation	3
Pothole	7
Total	**18**



Free Line (Hospital Road):

The following list of the failure kinds and their percentages:

Potholing (41%): Potholes dominate 41% of the road section, representing the most severe form of localized failure caused by structural fatigue, water ingress, and progressive disintegration of surface layers.

- **Edge Failure (23%)**: Edge-related failures affect 23% of the total road segment, primarily due to insufficient shoulder support, drainage inefficiencies, and lateral load-induced cracking.
- **Segregation (12%)**: Around 12% of the pavement area displays segregation of bituminous components, leading to material inconsistency and early-stage surface degradation.
- **Surface Wear and Tear (12%)**: General surface deterioration, including abrasive wear, minor stripping, and polishing, affects approximately 12% of the road, signifying prolonged exposure to traffic loading and environmental conditions.
- **Cracking (Block/Alligator Cracking) (12%)**: Block and fatigue (alligator) cracking patterns are present in 12% of the pavement, indicating repeated flexural stress and sub-base weakness.

Table 5: Frequency of defects in free line

Type of Failure	Frequency
Edge Failure	4
Segregation	2
Pothole	7
Cracking	2
Wear and tear	2
Total	**17**

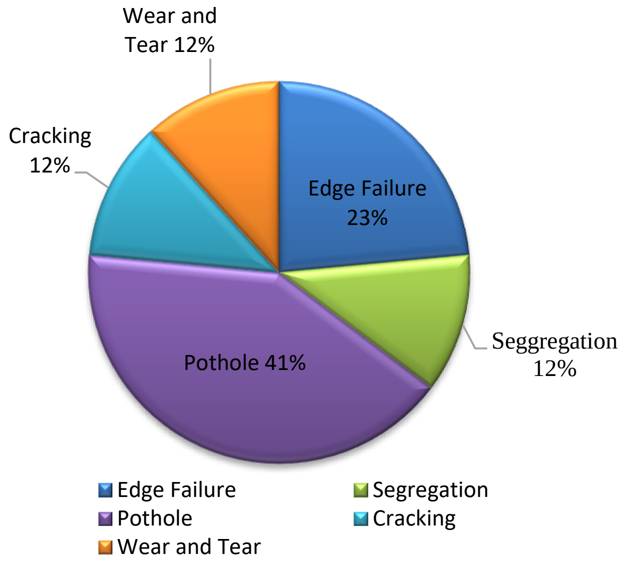


Figure 5: Percentage of failure in the free line

Overall Pavement Failure Condition

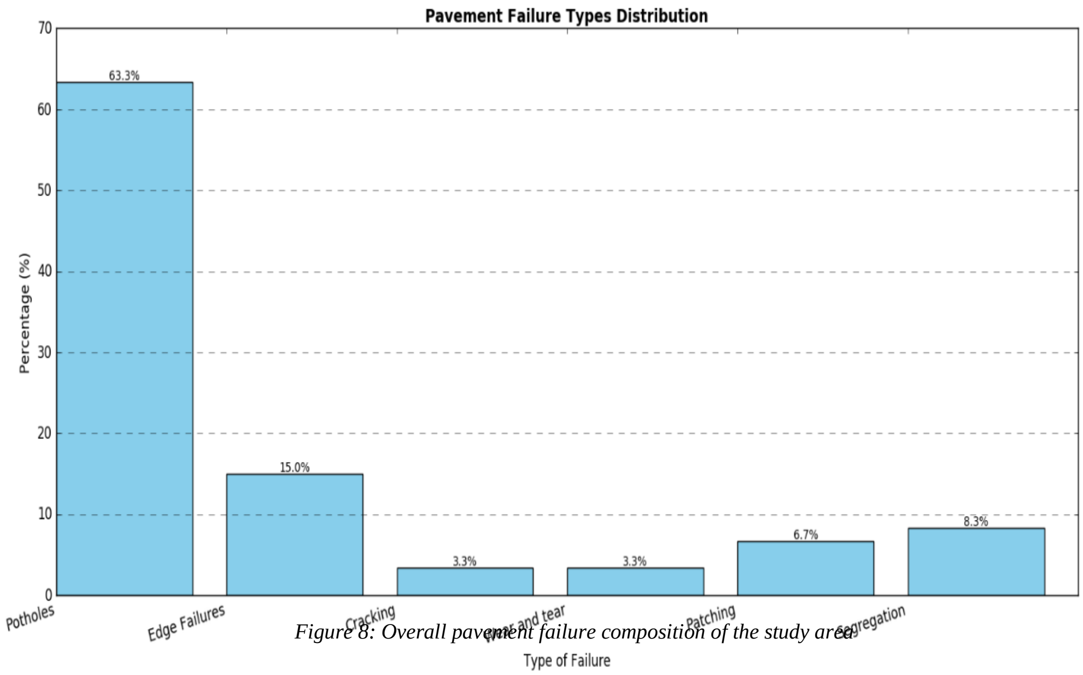


Figure 8: Overall pavement failure composition of the study area.

The overall flexible pavements failure status of all streets indicate that pavements are in poor condition, with potholes (63.3%) and edge failures (15%) being the most common issues. This suggests inadequate drainage, weak structural design, and poor maintenance practices. The presence of segregation (8.3%) and patching (6.7%) points to construction quality concerns and temporary repairs. Lower rates of cracking and wear imply less fatigue damage but may increase over time. Overall, the data highlights the urgent need for pavement rehabilitation, improved drainage, better construction standards, and the implementation of a pavement management system to ensure long-term road performance and safety.

Conclusion

This research comprehensively assessed the failure patterns of flexible pavements across six arterial streets in Mahendranagar City. The findings reveal that potholes and edge failures are the most prevalent distresses, primarily caused by inadequate drainage, poor-quality materials, and lack of timely maintenance. Streets 2, 3, 4, 5, and the Free Line showed varying levels of deterioration, while Street 1, being newly constructed, showed no visible defects. The severity of failures, especially on Streets 4 and 5, indicates structural fatigue and subgrade instability. The absence of preventive maintenance, coupled with climatic and traffic-induced stresses, exacerbates pavement degradation. This study concludes that a structured pavement management system, regular inspection, drainage upgrades, and durable rehabilitation techniques are critical to improving road longevity and ensuring user safety.

Recommendations

Since the nation's environmental issues, socioeconomic activity, lifestyle, and users fluctuate constantly, it is necessary to often enhance the maintained road condition. To keep the pavement in a safe and acceptable operating condition and reduce maintenance costs, the proper maintenance and repair work must be implemented promptly**.** Based on the outcomes of this research, the following table is recommended to all stakeholders to diagnose the causes of frequent failures along with maintenance suitability:

Table 6: Maintenance Proposed for the Pavement Failures in Each Street

Street	Dominant Failures	Recommended Solution	Reason for Selection
Street 2	Edge failure, cracking, potholes, wear & tear	Mill & Overlay with Edge Reinforcement	Multiple moderate failures suggest surface fatigue. A mill & overlay restores structural integrity. Edge failures require subgrade shoulder reinforcement.
Street 3	Potholes (55%), Edge Failure	Full-Depth Patching, Overlay, Edge Repair	High pothole rate indicates structural failure; full-depth patching needed. Overlay improves surface. Edge repair prevents water intrusion and

			slippage.
Street 4	Potholes (83%)	Full-Depth Reconstruction, Proper Drainage	Extremely high pothole percentage suggests deep subgrade failure. Full-depth reconstruction restores integrity. Drainage upgrade prevents recurrence.
Street 5	Potholes (39%), Edge Failure (22%)	Full-Depth Reclamation, Polymer Overlay, Geosynthetic Edge Stabilization	High pothole prevalence indicates subgrade failure; FDR rebuilds structurally. Polymer overlay resists cracking. Geosynthetics prevent edge erosion and water damage
Free Line	Potholes (41%), Edge Failure (23%)	Full-Depth Reclamation, Polymer Overlay, Geogrid Edge Reinforcement	High pothole percentage indicates base failure needing FDR. Polymer overlay prevents future cracks. Geogrid stops edge deterioration and water damage.

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Conflict of Interest

Authors declare that no conflict of interest exists.

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