



Pavement Failures and Their Remedies

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Abstract

Pavement failures remain a critical challenge in civil engineering and infrastructure development, particularly in rapidly growing countries like India. This paper investigates the underlying causes of pavement distress by combining practical insights from road construction projects with evidence gathered from existing research studies. Several case studies from highways across India are examined, where recurring pavement failures have been documented over the years. The findings highlight that most failures can be traced back to a few key factors: inadequate compaction of base and sub-base layers, improper design or execution of bituminous mixes with insufficient binder content, and the overlooking of essential design elements such as expansion joints. These construction-related shortcomings often manifest as surface cracks, potholes, rutting, and other visible forms of deterioration, which not only shorten the service life of pavements but also increase long-term maintenance costs. The paper emphasizes that with rising traffic volumes, the introduction of heavier vehicles, and the increasing impact of extreme weather conditions, constructing durable pavements has become more urgent than ever. Pavement design and construction should no longer be viewed as a purely technical activity but as a national priority that directly influences road safety, economic development, and sustainability. Through the analysis of case studies, patterns of common mistakes and oversights are identified, offering lessons for engineers and policymakers. The research suggests that adopting data-driven planning methods, selecting materials that are tailored to local environmental and traffic conditions, and instituting strict, periodic maintenance programs can significantly enhance pavement longevity.

Keywords: *Pavement failures, Cracks, Potholes, Rutting, Road maintenance, Asphalt, Concrete, Fatigue failure, Thermal cracking, Drainage issues, Subgrade weakness.*

Introduction

Roads are crucial to a country's growth they boost the economy, connect people, and provide access to important services. They support industries like agriculture, trade, tourism, and daily transportation. In India, rapid urban growth and economic development have led to a big increase in vehicles and freight movement. Over the past few decades, this demand has caused the road network to grow significantly. Today, national highways, state highways, and rural roads stretch for millions of kilometers and play a vital role in everyday life. However, keeping these roads in good shape remains a constant challenge. Many factors contribute to their deterioration over time. These include overloaded vehicles, poor-quality materials, flawed designs, and harsh weather. Maintenance is often delayed or ignored. Limited budgets, lack of supervision, and shortage of skilled staff make things worse. Because of this, roads that should last 10 to 15 years often start showing damage much sooner sometimes just a few years after they are built Improving pavement performance requires a comprehensive understanding of how these failures develop, along with a commitment to better planning, quality control, and regular maintenance. Sustainable materials, proper drainage systems, stricter vehicle load enforcement, and modern construction practices can all contribute to reducing early pavement failures and extending the life of road infrastructure.

Literature Review

The study of pavement failure has attracted considerable attention over the past decades as road networks grow and experience increasing traffic and environmental loads. Researchers have identified multiple factors responsible for pavement deterioration, ranging from improper material selection to inadequate drainage and overloading. This section presents a detailed review of scholarly work and guidelines that explore the causes and remedies of pavement failures. Yoder and Witczak (1975) [1], *Understanding Pavement Failure Mechanisms* in their classic text, emphasized that flexible pavements typically fail due to fatigue cracking, rutting, and surface wear. They highlighted how pavement design depends on traffic load, climate, and subgrade conditions. Poorly compacted base layers and inadequate structural capacity contribute significantly to premature failures. Khanna and Justo (2013) [2] supported this view, stating that fatigue and thermal cracking, potholes, and water-induced damage are commonly observed failures in flexible pavements. They stressed that these failures often stem from poor construction practices, incorrect layer thicknesses, and insufficient attention to drainage. Water ingress has long been identified as one of the most damaging elements for pavements. Kale and Deshmukh (2020) [3], *Drainage and Water Infiltration* conducted a field study in Maharashtra and concluded that clogged or missing side drains lead to edge cracking and subgrade softening. The presence of standing water was also associated with frequent pothole formation and pavement collapse in their observations. The Indian Roads Congress (IRC:37-2018) [4] highlighted similar concerns and mandated that drainage must be considered during both design and construction stages. It recommended providing proper cross slopes, longitudinal drainage, and shoulder drains to minimize moisture damage. According to the IRC: SP:16-2004 guidelines [5], crack sealing, patch repairs, and periodic surface dressing are essential treatments to prevent water from penetrating the pavement layers and affecting the subgrade.

With increasing axle loads, particularly in countries with poor regulation of commercial vehicles, pavements often suffer premature fatigue. The Ministry of Road Transport and Highways. MoRTH, (2022) [6], Traffic Loading and Structural Deficiency reported that over 40% of Indian highways face traffic loads exceeding their original design capacity, leading to early failure. Patel and Gupta (2019) [7] investigated flexible pavement sections in Gujarat and observed that overloaded trucks were the primary reason behind longitudinal cracking and rutting. Their results pointed toward a strong correlation between axle overloading and reduction in pavement lifespan. Substandard construction quality is another major cause of pavement failure. Babu, R., and Rao, V. (2018). [8], Poor Construction Practices found that improper compaction, use of low-quality aggregates, and lack of supervision were key reasons for surface and base course failures. The absence of field density checks and insufficient binder content often led to early cracking and loss of surface texture. The AASHTO (1993) [9] emphasized designing pavements with a safety margin and recommended extensive testing during construction. It stressed the importance of controlling variability in materials and ensuring that proper compaction, curing, and layer bonding is achieved in the field. Al Omari and Darter (1994) [10], Maintenance Strategies proposed the use of a Pavement Condition Index (PCI) as an effective tool to identify early-stage pavement distress. Their research demonstrated that timely interventions like crack sealing and surface treatments can delay the onset of structural failures and reduce life-cycle costs. The Indian Roads Congress, in its IRC: SP:16-2004 [5] document, outlined preventive maintenance treatments such as fog seal, slurry seal, and thin overlays. These methods are designed to restore surface integrity, improve skid resistance, and prevent water ingress. Singh et al. (2017) [11], Reinforcement and Innovations explored the use of geosynthetics in pavement construction and found that they significantly reduce surface deformation while also extending the service life of roads. Geotextiles, in particular, have proven to be an effective tool in both road construction and maintenance. When placed between pavement layers, they help distribute wheel loads more evenly, which reduces pressure on weak subgrades and minimizes rutting. This reinforcement improves the overall structural strength of the road. In areas with soft or moisture-sensitive soil, geotextiles provide much-needed support, helping to prevent early damage and reduce the frequency of repairs. Along with reinforcement methods, there's a growing focus on more sustainable and affordable ways to build roads. Recycling techniques like Reclaimed Asphalt Pavement (RAP) and cold in-place recycling are becoming increasingly popular. RAP means taking old asphalt from worn-out roads, grinding it up, and mixing it into new pavement layers. This cuts down on the need for new raw materials. Cold in-place recycling goes even further by repairing and rebuilding damaged road sections right where they are without heating the materials or hauling them away. These approaches not only help save money but also reduce the environmental footprint of road construction.

Classification of Pavement Failures

Pavement failure happens when the different layers of a road the ground beneath, the base, and the surface can't support the weight and traffic they were built to carry. This usually happens because of problems like poor design, using materials that aren't strong enough, shoddy construction work, or vehicles that are heavier than what the road

can handle. Typically, these issues begin deep down in the lower layers of the pavement and slowly make their way up, eventually becoming visible as cracks, potholes, or other damage on the road's surface.

Cracking

Fatigue cracking sometimes called alligator or crocodile cracking—is a common type of damage in flexible pavements. It shows up as a network of connected cracks, usually in the wheel paths, and happens because of repeated traffic loading over time. When the pavement isn't thick enough to handle the weight and volume of vehicles, tiny cracks start to form and eventually join together, creating this distinctive pattern.

- **Longitudinal Cracks:** These run along the direction of traffic and are often caused by poor joint construction or weak bonding between layers.
- **Transverse Cracks:** These run across the road, perpendicular to traffic flow, and are usually linked to temperature changes causing the pavement to expand and contract.
- **Alligator Cracks:** These interconnected cracks look like a crocodile's skin and indicate serious structural failure due to repeated stress from traffic.

Rutting

Rutting refers to the permanent deformation or depressions in the wheel paths of a flexible pavement. This type of failure often results from consolidation or lateral movement of the asphalt or subgrade layers. Rutting is dangerous because it can lead to water accumulation, which increases the risk of hydroplaning for vehicles. It typically indicates that the pavement structure lacks adequate stiffness or that there is poor drainage beneath the surface.

Potholes

Rigid pavements, primarily constructed of concrete, often suffer from failures such as pumping and faulting. Pumping occurs when water and fine materials are ejected from beneath the slab through joints or cracks due to heavy wheel loads. Faulting refers to vertical displacement at joints or cracks, where one slab becomes higher than the adjacent one. Both issues are signs of structural failure in the sub-base or subgrade.

Surface Wear

Functional failures do not necessarily indicate a weakness in the load-bearing capacity of the pavement but can still affect the safety, comfort, and performance of the roadway. These types of failures often occur due to environmental factors, poor surface maintenance, or aging.

- **Raveling:** Loss of aggregate particles from the surface. Indicates aging or poor mix.
- **Polishing:** Smooth, slippery surfaces formed due to traffic polishing aggregates, reducing skid resistance.



(Source: google)

Figure 2: Surface Wear.

Edge Breaks and Depressions

Thermal cracks develop due to temperature variations, especially in areas with hot days and cold nights. In asphalt pavements, these are usually transverse cracks running across the lane. They are more prevalent in climates with extreme seasonal or daily temperature changes.

Usually occur on narrow or poorly drained roads. Heavy loads near road edges can cause them to break away.

Causes of Pavement Failures

Understanding the causes of pavement failures is essential for engineers, road maintenance authorities, and planners to ensure long-lasting, safe, and cost effective road infrastructure. Pavement failure is rarely the result of a single factor; instead, it usually stems from a combination of design errors, poor construction practices, environmental influences, material defects, and improper maintenance. This section outlines the major causes behind flexible and rigid pavement failures observed in field conditions.

Inadequate Pavement Design

One of the most significant contributors to early pavement failure is improper structural design. When the design does not accurately account for actual traffic loading, axle weights, or subgrade support capacity, the pavement is more prone to fatigue cracking, rutting, and eventual structural collapse. For example, a pavement designed for light traffic but exposed to frequent heavy trucks will deteriorate prematurely.

Design standards such as the IRC:37-2018 provide guidelines for the thickness and composition of pavement layers based on anticipated traffic and soil properties. However, failures often occur when these standards are not properly followed, or if site conditions differ from those assumed during design (IRC:37-2018) [1].

Poor Quality of Construction

Construction quality plays a vital role in pavement performance. Improper compaction of subgrade, sub-base, and base layers can lead to differential settlements and eventual cracking. Similarly, inadequate bonding between layers, improper laying of bituminous mix, or insufficient curing in concrete pavements weakens the structural integrity.

Temperature control during asphalt laying is critical; if the bitumen cools before compaction, the resulting pavement is weak and porous. Similarly, improper joint construction in concrete pavements can lead to faulting and pumping. Many pavement failures in India have been traced back to construction lapses caused by time pressure, lack of skilled labor, or poor supervision during execution Rao et al., (2017) [2].



(Source: google)

Figure 3: Poor Quality of Construction.

Subgrade and Soil Issues

The strength and stability of subgrade soil directly affect pavement performance. Weak, expansive, or water-sensitive soils fail to provide adequate support and can deform under traffic loading. Clayey soils, in particular, swell when wet and shrink when dry, causing pavement heaving, longitudinal cracking, and uneven settlements. Inadequate subgrade preparation such as failure to remove organic or loose materials — also leads to early failure. Use of chemical stabilizers like lime or cement can improve subgrade quality, but this is often neglected in rural and low-volume roads Sharma and Gupta, (2015) [3].

Inadequate Drainage

Water is often referred to as the most destructive agent in pavement systems. Inadequate surface or subsurface drainage allows water to infiltrate the pavement layers, reducing the strength of the subgrade and base. In flexible pavements, this leads to stripping of bitumen from aggregates, weakening the asphalt layer. In rigid pavements,

moisture causes loss of support and slab faulting. Outlines drainage design considerations, but they are frequently ignored or poorly maintained in practice. Blocked side drains, lack of cross slope, or damaged shoulder edges often result in water accumulation and pavement deterioration IRC: SP:42-(2014) [4].

Traffic Overloading

Overloading of commercial vehicles beyond legal axle weight limits causes excessive stress on the pavement structure, especially on flexible pavements. Even a few passes of overloaded trucks can cause fatigue cracking, rutting, and deformation. Studies have shown that a single overloaded axle can cause damage equivalent to thousands of standard axle loads. Ghosh et al., (2016) [5].

Lack of enforcement of axle load regulations and high freight demands often lead to such conditions, especially on highways connecting industrial zones and ports.

Environmental Factors

Environmental conditions, including temperature fluctuations, rainfall, and freeze-thaw cycles, significantly influence pavement performance. In hot climates, high temperatures soften bitumen, leading to bleeding and rutting. In colder regions, freeze-thaw action can cause frost heaving and surface cracking, especially in rigid pavements.

Furthermore, seasonal variations in moisture affect the subgrade strength, causing pavement movement and cracking. UV radiation also contributes to bitumen aging and surface ravelling over time. Patel and Desai, (2014) [6].

Material Deficiencies

The selection of materials for pavement construction must adhere to specifications for strength, durability, and gradation. Use of substandard aggregates, bitumen with low penetration grade, or improperly graded base materials reduces the lifespan of pavements.

For example, aggregates with high water absorption are more prone to stripping, while poorly graded granular bases lead to uneven settlement. Also, bitumen with high wax content tends to harden quickly, increasing the risk of early cracking. IS:73-(2013) [7].

Lack of Timely Maintenance

Delayed or inadequate maintenance contributes significantly to the escalation of minor pavement defects into major failures. Surface cracks, if not sealed promptly, allow water infiltration, which damages underlying layers. Similarly, untreated potholes expand quickly under traffic loading.

Routine maintenance practices such as crack sealing, patching, fog sealing, and periodic resurfacing are essential to prolong pavement life. In many public road systems, however, maintenance budgets are limited or not efficiently utilized, leading to a "worst-first" approach rather than preventive care Rao and Iyer, (2012) [8].

Case Study: Pavement Failure on NH-48 (Ahmedabad–Vadodara Expressway), Gujarat, India

Background

The Ahmedabad Vadodara Expressway (NH-48) is a vital four-lane, 93-km corridor that connects two major cities in Gujarat, India. It handles a high volume of daily commercial and passenger traffic. Designed as a flexible pavement system with dense bituminous macadam and bituminous concrete surface layers, the expressway is expected to have a service life of 15–20 years under normal conditions. However, within just 7 years of operation, multiple sections of the expressway began to show signs of distress, raising concerns among engineers and commuters.

5.2 Observed Failures

Visual inspection and technical assessments identified the following pavement failures:

- Longitudinal and transverse cracking in several stretches
- Severe rutting in the outer lanes, especially near toll plazas and truck bays
- Potholes, edge breaking, and surface ravelling in high-traffic areas
- Waterlogging along shoulders, with signs of base layer pumping

These failures were more pronounced in sections exposed to consistent overloading by trucks and in areas with poor drainage. The damaged areas increased the risk of accidents, disrupted smooth traffic flow, and necessitated frequent patch repairs.

Investigation and Diagnosis

A detailed investigation was conducted jointly by the National Highways Authority of India (NHAI), Central Road Research Institute (CRRI), and an independent consultant. The team performed the following assessments:

- Core cutting to evaluate pavement layer thickness and material condition
- Falling Weight Deflectometer (FWD) tests to assess structural capacity
- Benkelman Beam Deflection (BBD) tests to determine residual life
- Subgrade soil testing for California Bearing Ratio (CBR)
- Drainage inspection and shoulder surveys

The study revealed the following critical issues:

- Pavement thickness was found to be 20–25% less than the design requirement in several places.

- Subgrade CBR values were much lower than assumed in the design (actual: 3–4%, assumed: 7%).
- Lack of proper camber and slope on shoulders led to water accumulation and infiltration.
- Poor-quality bitumen and uncrushed aggregates were used during construction, resulting in early aging and stripping.
- No weigh-in-motion systems were installed to monitor overloading at entry points.

5.5 Remedial Measures Taken

Following the investigation, a multi-level rehabilitation plan was implemented:

1. Overlay with Modified Bituminous Mixes: Distressed sections were milled and overlaid with a Polymer Modified Bitumen (PMB) mix for increased rutting resistance.
2. Full-Depth Reclamation (FDR): Severely damaged stretches were reconstructed using cement-treated base with FDR techniques.
3. Drainage Improvement: Shoulders were regraded, and side drains were deepened to eliminate water stagnation.
4. Traffic Load Monitoring: Weigh-in-motion sensors were installed at toll booths to monitor axle loads.
5. Preventive Maintenance Schedule: A routine maintenance plan was introduced, including crack sealing, fog sealing, and edge repair every 6 months. NHAI, (2024) [12].

5.6 Outcome

Post-rehabilitation, a noticeable improvement in pavement condition and ride quality was observed. Regular maintenance and better traffic enforcement helped reduce new damage. User satisfaction surveys indicated a 70% improvement in ride comfort and reduced travel delays.

This case demonstrates the importance of adhering to design standards, using quality materials, implementing drainage plans, and conducting regular maintenance to avoid costly pavement failures.

Methodology

The methodology for analyzing and addressing pavement failures on NH-48 involved a systematic approach combining site investigation, data collection, laboratory testing, and design evaluation. The key steps are described as follows:

Site Investigation and Data Collection

Initially, a thorough site inspection was conducted to identify visible signs of distress such as cracks, rutting, potholes, and surface deformation. The area's traffic characteristics were recorded, including vehicle types, traffic

volume, and the presence of overloaded trucks. Drainage conditions and environmental factors were also noted, as these play a crucial role in pavement performance.

Subgrade and Material Testing

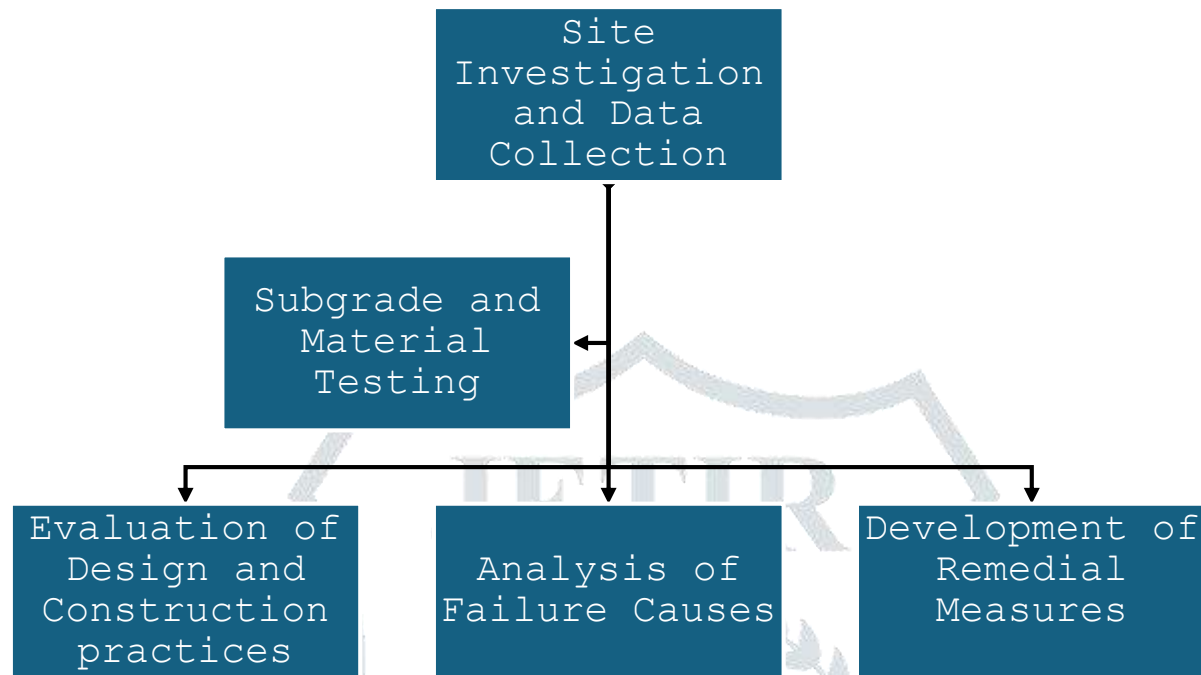


Figure 5: Flowchart of Methodology.

Samples from the pavement layers and subgrade were collected for laboratory testing to determine physical and mechanical properties. Tests included soil classification, California Bearing Ratio (CBR) to evaluate subgrade strength, and material gradation analysis. These results were compared against original design parameters to identify discrepancies.

Evaluation of Design and Construction Practices

The original pavement design was reviewed in detail, assessing whether it matched the actual site conditions and traffic loading. Construction records were examined to verify if proper materials and methods were used during pavement laying. Particular attention was given to quality control processes and compliance with relevant standards.

Analysis of Drainage and Maintenance

Drainage systems were inspected to assess their effectiveness in removing surface and subsurface water. Poor drainage was identified as a major contributor to pavement deterioration. Maintenance history was reviewed to determine if routine preventive actions were taken to address early signs of damage.

Identification of Failure Causes

By integrating the collected data, the main causes of pavement failure were identified. These included insufficient subgrade strength, overloading by heavy vehicles, use of substandard materials, poor drainage, and inadequate maintenance.

Development of Remedial Measures

Based on the failure analysis, suitable remedial measures were proposed to extend the pavement's service life. These included improving subgrade strength through stabilization, enhancing drainage infrastructure, enforcing load regulations, ensuring quality materials, and establishing regular maintenance programs.

Monitoring and Follow-up

A monitoring plan was recommended to track the effectiveness of implemented measures. This involved periodic inspections and performance evaluations to ensure early detection of potential issues and timely repairs.

Conclusion

Pavement failures continue to be a major concern for engineers, road authorities, and infrastructure planners. This study highlights how different types of pavement distress like cracks, rutting, potholes, and surface deformation often result from a combination of issues. These include poor construction practices, low-quality materials, inadequate pavement thickness, lack of proper drainage, and heavy traffic loads. When such problems aren't addressed early on, they can lead to unsafe roads, higher maintenance costs, and shorter pavement life. The research shows that identifying the root causes early through thorough inspections is key. On-site surveys, lab testing, and condition assessments help uncover both surface-level problems and deeper structural issues. For example, the case study on NH-48 reveals how poor drainage and unchecked vehicle overloading can lead to rapid deterioration, even when the original construction appears sound. Improving road performance requires a more preventive approach. This means enforcing quality control during construction, designing roads based on actual traffic and soil conditions, and using durable materials. Proper drainage systems and regular maintenance also play a crucial role in extending the life of pavements. In addition, continuous training for engineers, use of modern construction methods, and following national standards like IRC:37-2018 and IRC: SP:16-2004 can significantly improve the durability of road infrastructure. A shift from reactive to proactive maintenance not only saves costs in the long run but also makes roads safer for everyone. In short, pavement failures rarely come down to just one issue they're usually the result of several overlapping factors. With smarter planning, better construction practices, and timely intervention, these problems can be minimized, leading to stronger, longer-lasting roads.

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