

Developing a Comprehensive Road Design Model for Mitigating Pothole Formation in Newly Constructed Flexible Pavements: A Case Study of Machakos-Kangundo Road, Kenya

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Abstract

Premature pothole formation in flexible pavements remains a major challenge in road infrastructure management, leading to increased maintenance costs, reduced pavement service life, and compromised road safety. Although existing mechanistic-empirical pavement design approaches consider traffic loading and structural response, they often treat environmental conditions, material characteristics, and construction quality independently, limiting their ability to predict localized pothole development in tropical environments. This study developed an integrated model for enhancing road design against pothole formation using the Machakos-Kangundo Road in Kenya as a case study. A mixed-methods case study design was adopted, combining field investigations, laboratory testing, traffic surveys, pavement condition assessment, and spatial analysis. The 38 km road corridor was divided into 20 m chainages to determine pothole frequency and distribution. Laboratory tests included Atterberg limits, California Bearing Ratio (CBR), compaction characteristics, and asphalt core density, while traffic loading was evaluated using Equivalent Standard Axle Loads (ESALs). Environmental data comprising rainfall and temperature records were integrated with construction quality and pavement performance indicators to evaluate their influence on pothole development. The results showed that potholes were concentrated between chainages 18 + 000 and 24 + 000 km, corresponding to sections characterized by poor drainage, weak clayey subgrades, inadequate compaction, and high heavy-vehicle loading. Soaked CBR values ranged from 5.2% to 13.8%, while high plasticity indices and low compaction levels were strongly associated with increased pavement distress. Traffic projections classified the corridor as Traffic Class T3 with cumulative load-

ing between 4.65 and 5.73 million ESALs over a 15-year design period. Based on these findings, an integrated pothole susceptibility model incorporating traffic loading, environmental conditions, material properties, pavement performance indicators, and construction quality was developed. The model provides a practical framework for improving pavement design, optimizing maintenance strategies, and reducing premature pothole formation in tropical environments.

Keywords

Flexible Pavements, Pothole Formation, Mechanistic-Empirical Model, Moisture Damage, Pothole Susceptibility Index Model

1. Introduction

Road infrastructure plays a critical role in socio-economic development by facilitating mobility, trade, and regional integration [1]. In developing countries, substantial public investments are directed towards upgrading road networks to bitumen standards to improve accessibility and reduce transport costs [1]. However, the long-term performance of these investments is frequently compromised by premature pavement deterioration, particularly early pothole formation [2]. Such failures reduce pavement service life, increase maintenance expenditure, and pose significant road safety risks [2].

Flexible pavements are widely adopted due to their constructability and adaptability to varying traffic and environmental conditions. Nevertheless, they remain highly susceptible to surface distress when exposed to heavy traffic loading, adverse climatic conditions, marginal material quality, and construction-related deficiencies [3] [4]. Potholes typically develop following surface cracking, moisture ingress, and progressive loss of structural integrity, making them one of the most disruptive forms of pavement distress [3]. Their occurrence shortly after construction raises concerns regarding the adequacy of prevailing pavement design and quality control practices.

Previous studies have shown that pothole formation results from the interaction of traffic loading, material properties, environmental conditions, and construction practices [5] [6]. Heavy axle loads and high load repetitions accelerate fatigue cracking and permanent deformation, particularly in pavements with limited structural capacity [7]. Environmental factors, notably rainfall and inadequate drainage, promote moisture infiltration into pavement layers, reducing stiffness and accelerating stripping and crack propagation. Temperature variations influence asphalt binder rheology and pavement flexibility, while subgrade strength and material gradation determine the ability of the pavement structure to distribute traffic loads [8]. Construction practices such as compaction quality, layer thickness control, and drainage provision further influence in-service performance [6] [9].

Pothole formation in flexible pavements is a progressive failure process driven by the interaction of traffic loading, moisture ingress, material strength, and construction quality [10]. This mechanism is consistent with previous studies that identify cracking-moisture interaction and loss of structural support as the dominant pathway leading to pothole development [9].

The relationship between pothole density, rainfall intensity, and Equivalent Single Axle Loads (ESALs) supports findings demonstrating that moisture accelerates stripping and reduces stiffness in asphalt pavements, particularly under heavy traffic loading [9]. In contrast to temperate regions, where freeze-thaw effects dominate, in tropical environments, inadequate drainage, weak subgrade conditions, and construction-related variability play a more critical role in pavement deterioration [11]. These observations reinforce the need for integrated pothole prediction models that simultaneously account for traffic, environmental exposure, material properties, and construction quality [12]-[14].

Despite the availability of mechanistic-empirical design methods and AASHTO-based procedures, many existing approaches consider these influencing factors in isolation [15] [16]. As a result, they often fail to capture the combined and location-specific mechanisms that drive pothole development, particularly in tropical environments characterised by intense rainfall and rapidly increasing traffic volumes [17] [18]. Most pothole prediction models are also developed using data from temperate regions, limiting their applicability to tropical environments [17].

Review of Existing Pothole Prediction Models and Their Shortcomings

Existing pavement performance and pothole prediction models address pavement deterioration primarily through indirect indicators rather than explicitly modeling pothole formation [14]. Mechanistic-empirical design approaches and AASHTO-based procedures provide robust frameworks for structural pavement design; however, they largely focus on long-term fatigue cracking and rutting performance and may not adequately capture early surface failures driven by localized moisture ingress and drainage deficiencies [13] [15] [19]. Similarly, network-level models such as HDM-4 and pavement management systems are effective for maintenance prioritization but often rely on aggregated condition indices, limiting their ability to represent site-specific interactions between traffic loading, rainfall exposure, material variability, and construction quality [20]. Furthermore, many existing models consider traffic, environmental, and material factors independently, despite evidence that pothole formation results from their combined and interacting effects [21]. These limitations highlight the need for an integrated modeling approach capable of capturing the coupled influence of traffic loading, environmental exposure, subgrade strength, and construction practices, particularly under tropical conditions where moisture-related deterioration is dominant.

The Machakos-Kangundo Road in Kenya, upgraded to bitumen standard in 2018, provides a representative case of premature pothole formation in a newly constructed flexible pavement. Despite being designed for an expected service life

consistent with national standards, the road has experienced widespread pothole occurrence well before the end of its design period. This study addresses this challenge by developing a comprehensive road design model that integrates traffic loading, environmental conditions, material properties, and construction practices to mitigate pothole formation in newly constructed flexible pavements.

2. Materials and Methods

2.1. Study Area and Research Design

A mixed-methods approach combining qualitative and quantitative techniques was adopted to investigate pothole formation in flexible pavements. Qualitative data captured road users' perceptions of pavement condition and safety, while quantitative data were used to analyse pothole characteristics, traffic loading, pavement materials, and environmental conditions.

A case study design was employed using the Machakos-Kangundo Road in Machakos County, Kenya. The corridor carries mixed traffic dominated by public transport vehicles and freight traffic. The road is exposed to variable climatic conditions. Meteorological data, including rainfall and temperature, were obtained from a weather station situated at Machakos, which were aggregated into monthly averages. The temperature and rainfall data were considered for the year between 2017 and June 2024.

2.2. Field Surveys and Data Collection

The road corridor was divided into 20 m chainages to enable accurate localization of potholes and sampling points. Field surveys conducted at each of the chainages documented pothole dimensions, frequency, and spatial distribution using a standardised checklist. Potholes of a minimum size of $500 \times 200 \times 50$ mm (length $\times$ width $\times$ depth) were included in the survey.

Traffic counts and environmental measurements were conducted at three representative locations: Machakos (0 + 200), Kenol (11 + 000), and Kangundo (20 + 000). Traffic and axle load measurements involved capturing the volume, classification, and physical weight of vehicles. In the representative locations, three stations were set up, and the vehicles were predefined into classes of cars, vans, small trucks, buses, medium trucks (2 axles), heavy trucks (4 or more axles), and oil tankers. The traffic counts were done in 24 hours for 4 consecutive days by traffic enumerators. This enabled the calculation of the Average Daily Traffic (ADT). In order to obtain the Average Annual Daily Traffic (AADT), the ADT values were multiplied by passenger car equivalent together with monthly expansion factors specified in the Kenya Road Design Manual [22].

The Equivalent Standard Axle Load (ESAL) was determined using the axle load equivalency factors prescribed in the design manual [22]. To determine the Cumulative Equivalent Standard Axles (CESA), three traffic growth scenarios (low, medium, and high) were considered and projected for a 15-year design period.

2.3. Laboratory Testing

Laboratory tests were conducted to determine material properties influencing pavement performance, including Atterberg limits, California Bearing Ratio (CBR), bitumen penetration, Marshall stability, and aggregate impact value. Testing followed relevant standards to ensure consistency and reliability of results [23]-[26].

2.4. Pavement Condition and Structural Assessment

GIS-based analysis was used to evaluate road classification, pavement type, and condition. Pavement coring was undertaken to determine actual layer thickness and material conformity according to [25]. Pavement performance was assessed using standard indicators, including International Roughness Index (IRI), Present Serviceability Index (PSI), Pavement Condition Index (PCI), rutting depth, cracking index, and pothole density in line with established pavement performance evaluation frameworks [27].

2.5. Model Formulation

A comprehensive pothole formation model was developed using a hybrid analytical approach that integrates regression modeling and a mechanistic-empirical framework. Regression modeling was applied to quantify relationships between traffic load, subgrade strength, rainfall, and pavement condition. The mechanistic approach enabled the inclusion of material properties and structural behavior of pavement to loading. The general form of the model was expressed using Equation (1):

$$P_d = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \varepsilon \quad (1)$$

where P_d is pothole density, X_1 axle load, X_2 subgrade CBR, X_3 rainfall intensity, X_4 pavement age, β_i regression coefficients, and ε the error term.

Model Architecture:

The flowchart shown in **Figure 1** has three main sections, namely, the input layer, the Mechanistic-Empirical modeling, and the formation of the comprehensive model. At the input stage, raw variables were input as collected from the road chainages. The mechanistic-empirical (ME) modeling computed the structural damage caused to the road corridor from the effects of traffic and material stiffness. The damage predicted by the ME was amplified by rainfall intensity and drainage inefficiency. The construction defect factor adds a consideration for under-compaction, uneven layer thickness, poor tack coat, and the observed quality assurance and control practices. Finally, in order to get a numerical score representing the likelihood of pothole formation, the construction quality was integrated into the ME modeling.

3. Results and Discussion

3.1. Road Network and Pavement Characteristics

The Machakos-Kangundo road comprises a two-lane flexible pavement carrying mixed traffic, with the dominant being 14-seater matatus, heavy commercial trucks,

and motorcycles. **Table 1** summarizes the observed site-specific factors.

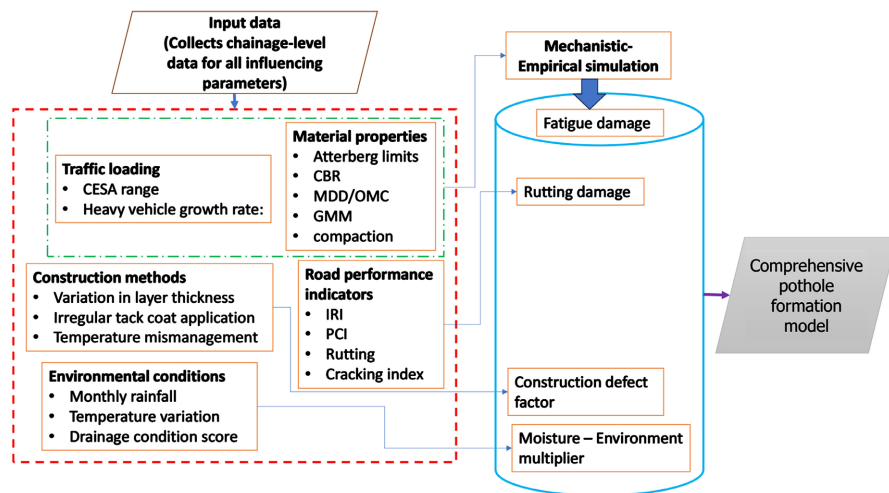


Figure 1. Flowchart for the comprehensive pothole formation model.

Table 1. Observed site-specific factors along the Machakos-Kangundo road.

Chainage (Km)	Pothole Frequency (Per 20 m)	Interpretation	Drainage Condition	Construction Deficiency	Remarks
1 + 000 - 2 + 000	37	Moderate distress	Silted drains	Asphalt segregation	Adjacent to the town center
2 + 000 - 4 + 000	60	High distress	Poor	High air voids	High risk of pavement failure
4 + 000 - 6 + 000	46	Moderate distress	Blocked drains	Low compaction	High risk of pavement failure
6 + 000 - 8 + 000	47	Moderate distress	Blocked drains	Low compaction	High risk of pavement failure
8 + 000 - 10 + 000	39	Low-moderate distress	Blocked drains	Low compaction	High risk of pavement failure
10 + 000 - 12 + 000	60	High distress	Poor	Low compaction	High risk of pavement failure
12 + 000 - 14 + 000	39	Low-moderate distress	Blocked drains	Asphalt segregation	High risk of pavement failure
14 + 000 - 16 + 000	49	Moderate distress	Blocked drains	Low compaction	High risk of pavement failure
16 + 000 - 18 + 000	44	Moderate distress	Blocked drains	Low compaction	High risk of pavement failure
18 + 000 - 20 + 000	70	Severe distress	Poor	Low compaction	Frequent water stagnation
20 + 000 - 22 + 000	72	Severe distress	Poor	Low compaction	Frequent water stagnation
22 + 000 - 24 + 000	78	Severe distress	Poor	High air voids	Frequent water stagnation

Continued

24 + 000 - 26 + 000	65	Severe distress	Poor	High air voids	Frequent water stagnation
26 + 000 - 28 + 000	70	Severe distress	Poor	Low compaction	Frequent water stagnation
28 + 000 - 30 + 000	63	Severe distress	Poor	Low compaction	High risk of pavement failure
30 + 000 - 32 + 000	66	Severe distress	Poor	High air voids	High risk of pavement failure
32 + 000 - 34 + 000	47	Moderate distress	Blocked drains	Asphalt segregation	High risk of pavement failure
34 + 000 - 36 + 000	53	Moderate distress	Blocked drains	Low compaction	High risk of pavement failure
36 + 000 - 38 + 000	28	Low distress	Silted drains	Asphalt segregation	High risk of pavement failure

As illustrated in **Figure 2**, pothole frequency peaks sharply between chainages 18 + 000 and 24 + 000 km, where frequencies exceed 70 potholes per 20 m. These sections coincide with poor surface drainage, soft subgrade conditions, and visible structural degradation. These findings demonstrate that pothole formation is governed by localised structural and environmental conditions rather than uniform pavement ageing.

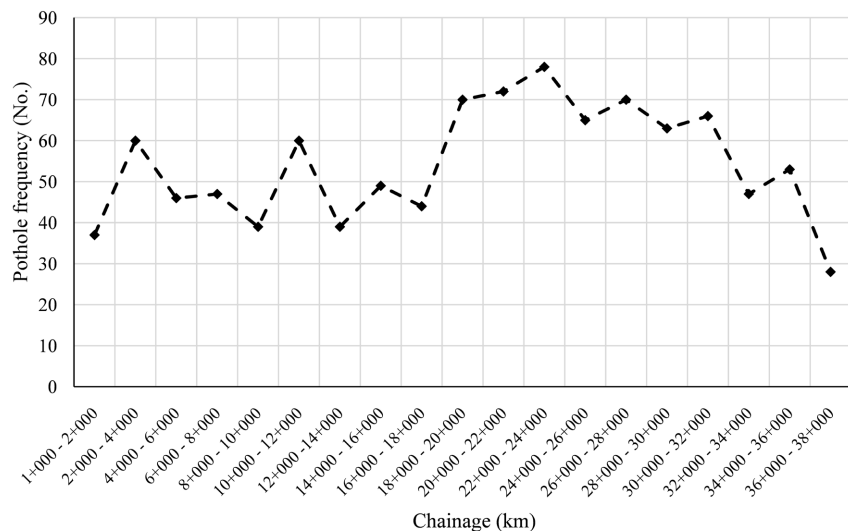


Figure 2. Pothole frequency distribution along the Machakos-Kangundo road chainages.

3.2. Influence of Environmental Conditions

As observed by Hamzah *et al.* [28], temperature and rainfall variations affect asphalt stiffness, moisture infiltration, and subgrade performance. The results presented in **Table 2** indicate bimodal rainfall patterns (April and December peaks), with temperature ranging from 16.9° to 21.5°. These variations, though not ex-

treme, are sufficient to influence asphalt binder stiffness and flexibility as noted by [28]. High temperature has been argued to cause weakening of flexible pavements and cause cracking of the asphalt through thermal expansion and contraction [29]. Conversely, rainfall saturates through the existing cracks, creating a weakened base layer that is susceptible to damage from continuous loading by the traffic. It can therefore be inferred from these results that this weather pattern provides a conducive environment for pothole formation and propagation along the Machakos-Kangundo road.

Table 2. Average monthly temperature and rainfall along the Machakos-Kangundo road.

Month	Rainfall (mm)	Temperature (°C)
January	100	18.9
February	70	20.3
March	20	20.9
April	330	18.5
May	140	18.6
June	70	18.2
July	20	16.9
August	20	18.1
September	30	20.0
October	200	21.5
November	270	18.4
December	350	19.8

To quantify the relationship between pothole formation and influencing variables, a correlation and regression analysis were performed using data on pothole frequency, drainage condition, rainfall, and construction deficiencies as presented in **Table 3**.

Table 3. The contributing effect of hydrological and construction deficiencies in pothole formation.

Variable Pair	Correlation Coefficient (r)	Relationship
Pothole frequency vs drainage condition	0.83	Strong positive correlation
Pothole frequency vs rainfall	0.76	Strong positive correlation
Pothole frequency vs compaction quality	-0.68	Strong negative correlation
Pothole frequency vs temperature	0.21	Weak positive correlation

3.3. Pavement Performance Indicators

Pavement condition indices showed progressive deterioration from Machakos towards Kangundo, as shown in **Table 4**. The progressive increase in International

Roughness Index (IRI) values from Machakos to Kangundo section suggests a consistent decline in surface smoothness due to accumulated pavement distress, particularly rutting and cracking. This pattern aligns with the field observations where increased traffic loading and inadequate drainage around the Kangundo area contributed to surface unevenness and reduced comfort levels.

Table 4. Pavement performance indicators for the Machakos-Kangundo road.

Section	IRI (m/km)	PSI	PCI	Mean Rut Depth (mm)	Cracking Index (%)	Serviceability Level
Machakos	2.8	3.9	82	6	12	Good
Kenol	3.5	3.2	71	8	18	Fair
Kangundo	5.8	2.4	48	15	34	Poor

According to [27], Present Serviceability Index (PSI) values below 2.5 indicate the need for immediate maintenance or rehabilitation. Therefore, the Kangundo section requires priority intervention to restore it to acceptable serviceability levels. The results demonstrate a strong negative correlation between PSI and IRI. Similarly, the cracking index's sharp increase from 12% to 34% across the same sections illustrates growing loss of pavement integrity.

3.4. Traffic Volume and Loading Characteristics on Pavement Condition

A critical finding of the volume characteristics along the corridor indicates that the Kangundo section, as shown in **Figure 3**, carries 8.52% more heavy goods vehicles compared to the Machakos section. This explains the heightened distress, higher rut depths, and reduced pavement performance indices along this section.

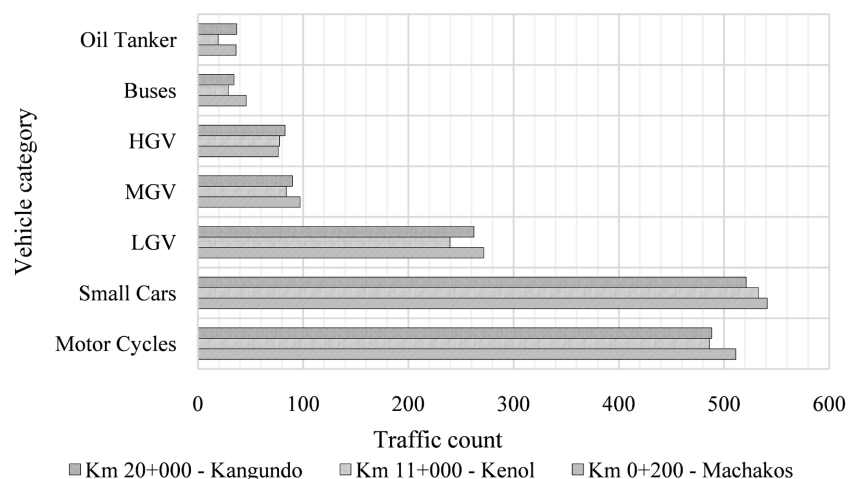


Figure 3. Average daily traffic by vehicle category along the Machakos-Kangundo road.

In order to allow for evaluation of cumulative pavement loading under different

traffic growth conditions, the Equivalent Standard Axle Loads (ESAL) were determined using the axle load equivalency factors prescribed in [30].

The Daily Equivalent Standard Axles (DESA) for the Machakos-Kangundo road represented a moderately trafficked Class T3 roadway according to [30]. Importantly, as shown in **Table 5**, projections under various growth scenarios (low 4%, medium 5%, and high 6%) showed a steady rise in DESA to the year 2027. This growth pattern demonstrates not only the increasing traffic burden but also the accelerating deterioration rate expected over the Machakos-Kangundo corridor.

Table 5. Traffic loading and cumulative equivalent standard axles for the Machakos-Kangundo road.

Determination of Cumulative Equivalent Standard Axles											
	MC	C	LGV	MGV	HGV	B	OT	Total	Traffic Growth Rates		
									Low	Medium	High
									(4.0%)	(5.0%)	(6.0%)
ADT	495	532	258	90	79	36	31	1521			
Seasonal Factors	1	1	1	1	1	1	1				
AADT	495	532	258	90	79	36	31	1521			
PCU C. F	1.5	1.5	3.0	10.0	20.0	6.0	20.0				
AADT (PCU)	743	797	773	904	1578	218	614	5627			
Equivalent Standard Axles Factor				1	4	1	4				
DESA at Initial Year (2024)				90	316	36	123	565			
DESA at Base Year (t1)—(2027)									636	655	674
CESA (X 10 ⁶), for a 15-Year Design Period									4.65	5.16	5.73
80% of CESA									3.719	4.127	4.581
Traffic Class									T3	T3	T3

3.5. Subgrade and Material Properties

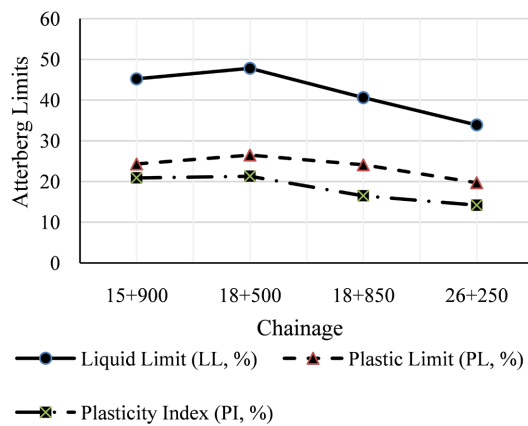
The Atterberg Limit values indicate that the subgrade soils along the Machakos-Kangundo road predominantly fall within the medium to high plasticity range, consistent with the AASHTO classification system, as shown in **Table 6**.

The trend depicted in **Figure 4(a)** confirms the presence of highly plastic clayey soils between chainages 18 + 000 and 24 + 000 km.

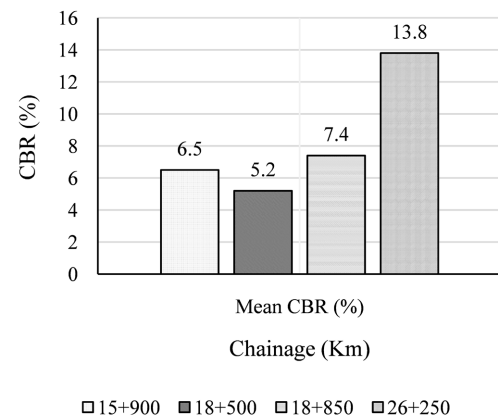
Subgrade soils exhibited poor to fair strength as expressed in **Figure 4(b)**, with CBR values ranging between 5% and 14%. This indicated limited structural support by the subbase. The variability in compaction quality and pavement layer thickness (**Figure 5(a)** and **Figure 5(b)**) indicated further reduced pavement structural capacity. These deficiencies, when combined with moisture ingress and heavy traffic loading, created favourable conditions for premature pothole formation, in agreement with the findings of [8].

Table 6. Atterberg limits at various sections of the Machakos-Kangundo road.

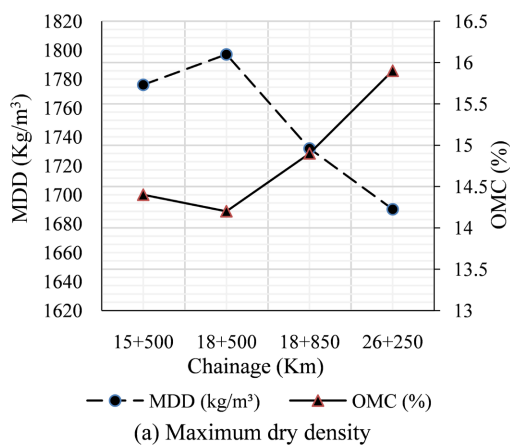
Chainage (Km)	Liquid Limit (LL, %)	Plastic Limit (PL, %)	Plasticity Index (PI, %)	AASHTO Classification	Remarks
15 + 900	45.2	24.3	20.9	A-7-6	Highly plastic clay; poor drainage and high swelling potential; corresponds to a high pothole frequency zone.
18 + 850	40.6	24.1	16.5	A-6	Moderately plastic soils; fair subgrade strength but sensitive to saturation under prolonged wet conditions.
26 + 250	33.9	19.7	14.2	A-4	Low plasticity soil with good drainage; stable subgrade and reduced surface distress.



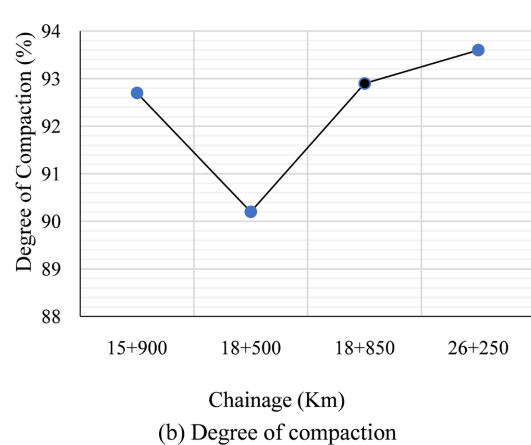
(a) Atterberg limits



(b) CBR variations

Figure 4. Variation of Atterberg limits and CBR on Machakos-Kangundo road.

(a) Maximum dry density



(b) Degree of compaction

Figure 5. Variation of maximum dry density, optimum moisture content, and degree of compaction along the Machakos-Kangundo road.

The General Marshall Mix (GMM) value of 2.37 g/cm³ indicates a moderately dense and well-designed asphalt mixture that conforms to the requirements of conventional bituminous surfacing [22]. This suggests that, at the material design stage, the asphalt mixture was structurally sound and suitable for use under medium to heavy traffic loading.

The core density values shown in **Table 7** revealed that the degree of compaction and air voids fall within the acceptable limits recommended by [27]. Confirming that most pavement sections achieved satisfactory field compaction.

3.6. Construction Methods

The assessment of construction methods established a direct relationship between workmanship quality and pavement deterioration patterns (**Table 8**). The most significant deficiencies—namely, undercompaction, inadequate drainage management, and temperature mismanagement during asphalt laying—accelerated the degradation process, consistent with the observed pothole distribution and core density results.

Table 7. Core density results and degree of compaction.

Chainage (km)	Core Density (g/cm ³)	GMM (g/cm ³)	Compaction (%)	Air Voids (%)	Interpretation as per AASHTO (1993)
15 + 900	2.196	2.37	92.7	7.3	Within acceptable range (well compacted)
18 + 500	2.137	2.37	90.2	9.8	Below spec; low compaction
18 + 850	2.201	2.37	92.9	7.1	Within acceptable range
26 + 250	2.218	2.37	93.6	6.4	Adequately compacted

Table 8. Summary of construction aspects evaluated.

Parameter	Field Observation/Test Result	Remarks/Implication
Compaction control	Inconsistent compaction across chainages; degree of compaction 90 - 94%	Localized under-compaction contributed to the early pothole initiation
Asphalt layer thickness	Nominal thickness 50 mm; variations up to ±10 mm	Uneven thickness led to differential stress distribution
Base/Sub-base compaction	Density averaged 97%; weak points near drainage outlets	Localized settlements linked to poor moisture control
Drainage installation	Side drains silted in several sections	Poor drainage accelerated stripping and pothole formation
Prime/Tack coat application	Irregular application rate; dry joints in some areas	Inadequate bond between layers encouraged delamination
Construction supervision	Limited QA/QC documentation observed	Reduced quality control led to variable field performance
Temperature control (Asphalt)	Mixing and laying temperatures are not consistently monitored	Cold joints and segregation in some sections

3.7. Pothole Formation Model

Using the field and laboratory findings, the developed model helps to estimate pothole susceptibility and expected pothole density by integrating environmental conditions, traffic loading, material properties, road performance indicators, and construction methods. The Mechanistic-Empirical damage modeling enabled the prediction of pavement performance through consideration of two types of damage: fatigue damage and rutting damage.

Fatigue Damage

The ME damage modeling predicted the damage fatigue as a function of cumulative equivalent standard axles (CESA) and the allowable load repetitions on the road corridor. The allowable load repetition values were calibrated using the CBR and the PCI trends observed in the results analysed. The damage was therefore calculated using Equation (2).

$$D_{fatigue} = \frac{CESA}{N_f} \quad (2)$$

where,

CESA—cumulative equivalent standard axles;

N_f —number of repetitions up to fatigue cracking (calibrated as a function of CBR and PCI trends).

Rutting Damage

The road performance indicators expressed the condition of the road in relation to the comfort of use. The ME modeling predicted the permanent deformation due to cracking and the vertical ruts created on each layer. The empirical rut depth takes into account the resilient modulus of each layer by incorporating the road performance indicators as shown in Equation (3).

$$R(mm) = \alpha CESA^\beta \left(\frac{1}{CBR} \right)^\gamma \quad (3)$$

where,

R—predicted rut depth (mm);

CESA—cumulative equivalent standard axles;

CBR—soaked California Bearing Ratio (%) of the subgrade;

α, β, γ —empirical parameters to be calibrated (rut depth data (6 - 15 mm) were used to calibrate coefficients).

3.7.1. Quantification of Drainage and Construction Quality Variables

Drainage Condition Score

The three road sections were assigned a drainage condition score (DCS) at intervals of 0.25. The drainage condition score was then incorporated into the moisture-environment multiplier to reflect the role of water infiltration in pothole development.

Moisture-Environment Multiplier

In order to quantify the combined effect of rainfall and drainage performance

on pavement deterioration, a moisture-environment multiplier (MEM) was developed using Equation (4). This multiplier combined the effect of recorded average monthly rainfall and the drainage condition score.

$$MEM = 1 + a \left(\frac{R}{R_{\max}} \right) + b(1 - DCS) \quad (4)$$

where,

MEM—moisture-environment multiplier;

R—average monthly rainfall (mm);

*R*_{max}—maximum rainfall recorded during the study period;

DCS—drainage condition score;

a—rainfall coefficient (calibrated to 0.40);

b—drainage coefficient (calibrated to 0.60).

On replacing the calibrated values of rainfall and drainage coefficient, Equation (4) can be written as Equation (5).

$$MEM = 1 + 0.4 \left(\frac{R}{R_{\max}} \right) + 0.6(1 - DCS) \quad (5)$$

3.7.2. Construction Defect Factor

A construction defect factor (CDF) was established in order to combine the degree of compaction, layer thickness variation, tack coat quality, temperature control during asphalt laying, and construction quality assurance practices. First, a construction quality index (CQI) was calculated using Equation (6).

$$CQI = \frac{\sum S_i}{n} \quad (6)$$

where,

S_i—score for each construction parameter;

n—number of parameters evaluated.

Then, the construction defect factor (CDF) was determined using Equation (7).

$$CDF = 1 - CQI \quad (7)$$

Integration into the effective damage model, the overall structural deterioration index becomes (Equation (8)).

$$D_{\text{eff}} = D_{\text{fatigue}} * MEM * (1 + CDF) \quad (8)$$

where,

D_{fatigue}—traffic-induced structural damage;

MEM—environmental and moisture effect;

CDF—construction-related defects.

3.7.3. Weighting of the Variables

All variables incorporated in the pothole susceptibility index (PSI) model were normalized using min-max scaling to eliminate unit inconsistencies and ensure comparability. The weighting factors were derived through a hybrid approach combining observed statistical relationships between pothole density and explan-

atory variables with established pavement engineering principles. Structural damage, subgrade strength, and pavement condition exhibited the strongest influence on pothole formation and were therefore assigned higher weights. This approach converts previously descriptive variables into measurable and repeatable model inputs.

Considering the weighted factors, the comprehensive pothole formation model is therefore estimated using Equation (9). The equation estimates the PSI, which integrates the parameters measured and observed in the study.

$$PSI = 0.28D_{eff} + 0.18(1 - CBR) + 0.12PI + 0.12Airvoids + 0.18IRI + 0.12CD \quad (9)$$

The comprehensive pothole formation model successfully captures the combined effects of traffic loading, soil loading, soil plasticity, moisture susceptibility, pavement condition, and construction quality. The implementation of the model can be integrated with the suggested classification of PSI values summarized in **Table 9**.

Table 9. Classification values for the pothole formation model.

PSI Value	Susceptibility Level	Interpretation
<0.25	Low	Good pavement condition
0.25 - 0.50	Moderate	Watch areas
0.50 - 0.75	High	Requires intervention
≥0.75	Very high	Pothole hotspot

4. Conclusions

This study developed a comprehensive mechanistic-empirical model to explain and predict premature pothole formation in newly constructed flexible pavements, using the Machakos-Kangundo Road in Kenya as a representative case. The findings demonstrate that early pothole development results from the interaction of heavy axle loading, rainfall-induced moisture ingress, weak and moisture-sensitive subgrade soils (CBR 5% - 14%), and localized construction deficiencies, rather than from isolated structural factors.

The analysis confirmed that potholes were highly clustered in sections characterized by poor drainage, increased Equivalent Standard Axle Loads, and reduced pavement condition indices (IRI, PCI, PSI). Laboratory and field results consistently showed that low subgrade strength, high plasticity, variable compaction, and inadequate moisture control significantly reduce pavement durability under tropical climatic conditions.

The proposed Pothole Susceptibility Index (PSI) model integrates traffic loading, environmental exposure, structural capacity, and construction quality into a unified predictive framework. Subgrade strength, drainage performance, and heavy vehicle loading emerged as the most influential determinants of pothole formation. By linking mechanistic damage accumulation with observed field performance, the model provides a practical decision-support tool for resilient pavement design.

and targeted maintenance planning.

Adoption of integrated, climate-responsive pavement design and stricter quality control practices is essential to mitigate premature pothole formation and enhance the sustainability of road investments in tropical developing regions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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