Continental J. Applied Sciences
Olotu et al. (2025) 20 (2): 78 – 95 Doi: 10.5281/zenodo.16732632

Research Article

Impact of Seasonal Flooding on Flexible Pavement Performance in Southwestern Nigeria

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Abstract

Seasonal flooding significantly undermines the performance and longevity of flexible pavements in Southwestern Nigeria, where intense rainfall, poor drainage, and weak subgrade materials exacerbate pavement deterioration. This study investigates the effects of flood events on pavement structures through field surveys, deflection testing, and geotechnical analyses in Lagos, Oyo, and Ogun States. The research identifies key distress mechanisms such as rutting, cracking, and subgrade softening caused by prolonged water exposure, confirming that flood duration and intensity directly correlate with decreased structural integrity. Laboratory tests reveal that post flood California Bearing Ratio (CBR) values declined by up to 45%, while Falling Weight Deflectometer (FWD) deflections increased by 30%, signaling substantial strength loss. A multivariate regression model was developed to predict Pavement Condition Index (PCI) based on flood variables, achieving a strong correlation (R^2 = 0.87). The study also evaluates economic impacts, estimating that flood damaged roads incur 40–50% higher rehabilitation costs. Mitigation strategies, including enhanced drainage design and use of resilient materials, are recommended. Findings support the need for policy reforms and adaptive pavement design to improve infrastructure resilience in flood prone areas of Nigeria.

Keywords: flexible pavement, seasonal flooding, pavement performance, Nigeria, subgrade failure, CBR, PCI, road infrastructure resilience

Received: 17 April 2025 **Accepted: 26 July 2025**

ISSN: 3043–6087. Science and Education Development Inst., Nigeria

Citation: Olotu, T, O., Oyewo, S.T., and Omoniyi, O. (2025). Impact of Seasonal Flooding on Flexible Pavement Performance in Southwestern Nigeria. Continental J. Applied Sciences, 20(2), 78–95. Doi: 10.5281/zenodo.16732632

Introduction

Seasonal flooding poses a significant challenge to road infrastructure in many parts of the world, particularly in regions with tropical climates. Southwestern Nigeria, characterized by its distinct wet and dry seasons, experiences regular flooding events that can severely impact the performance and longevity of flexible pavements. This study aims to evaluate the extent of this impact and develop strategies to mitigate the adverse effects of flooding on road infrastructure. The objectives of this research are to: (i) Assess the performance of flexible pavements before, during, and after flooding events in Southwestern Nigeria. (ii) Analyze the environmental factors contributing to pavement deterioration during floods. (iii) Evaluate the economic implications of flood induced pavement damage. (iv) Develop mitigation strategies and design recommendations for flood resilient pavements. (v) Create a predictive model for pavement performance under various flooding scenarios.

Understanding the relationship between seasonal flooding and pavement performance is and crucial for developing sustainable road infrastructure in flood prone regions. This study's findings will contribute to improved road design practices, maintenance strategies, and policy recommendations for areas susceptible to regular flooding. Seasonal flooding severely impacts the performance of flexible pavements in tropical regions like Southwestern Nigeria, where high rainfall and poor drainage systems lead to moisture infiltration, subgrade weakening, and surface distress (Huang, 2004; Olubajo and Oke, 2015). Studies show that CBR values can drop by up to 50% after flooding, while deflection increases significantly, reducing structural capacity and ride quality (Adebayo et al., 2020; Mamlouk and Zaniewski, 2011). Inadequate consideration of hydrological factors in Nigerian pavement design further compounds these issues (FMWH, 2013; Osuolale et al., 2019).

International studies echo similar challenges. For instance, flood-induced pavement failures in Ghana and India have reduced road lifespan by up to 40% and 35%, respectively (Osei, 2019; Pandey et al., 2018). In Nigeria, inadequate stormwater systems and poor drainage increase pavement vulnerability, with many roads failing within five years due to the absence of flood assessments (NBRRI, 2019; Adebayo et al., 2020). This highlights the urgent need for localized flood-resilient road designs. Current Nigerian standards lack specific flood resilience guidelines, unlike international standards like AASHTO, which recommend moisture-sensitive design parameters (FMWH, 2013; AASHTO, 2017; Olowosulu and Akinwumi, 2018). Incorporating hydrological data, improved drainage, and water-resistant materials can greatly enhance road durability.

Maintenance remains reactive, expensive, and delayed by limited funding and institutional inefficiencies (Olojede and Odetunmibi, 2021). Proactive measures such as preventive sealing, drainage restoration, and real-time monitoring are rarely implemented due to technical and financial constraints. Moreover, a lack of predictive models tailored to Nigeria's climate and soil conditions hinders planning. Existing models like AASHTO and HDM-4 are often ineffective locally (Okonkwo and Ezeh, 2022). Developing empirical models that correlate flooding variables with pavement performance, using tools like GIS and machine learning, is essential for sustainable, climate-resilient infrastructure.

Materials and Methods

This study employed a mixed method approach combining field investigations, laboratory testing, and statistical modeling to assess the impact of seasonal flooding on flexible pavement performance in Southwestern Nigeria. Three flood prone states, Lagos, Ogun, and Oyo, were selected based on flood frequency, traffic volume, and pavement failure records. Geospatial analysis using GIS tools and Digital Elevation Models (DEMs) helped identify vulnerable road segments and low-lying areas.

Data were collected from multiple sources, including meteorological agencies (rainfall and flood records), transportation authorities (traffic and pavement history), and field surveys (visual inspections and GPS mapping). Key geotechnical indicators; California Bearing Ratio (CBR), subgrade moisture content, and deflection, were measured using Dynamic Cone Penetrometer (DCP) and Falling Weight Deflectometer (FWD) equipment.

A multivariate regression model was developed to predict Pavement Condition Index (PCI) using variables such as flood duration, traffic intensity, and soil strength. The model's reliability was evaluated using R^2 and RMSE metrics. Life cycle cost analysis (LCCA) and environmental impact assessments were also conducted to evaluate the long term implications of flood damage on road infrastructure. This comprehensive methodology ensures both technical robustness and practical relevance in understanding flood induced pavement deterioration.

Study Area Definition

The study was carried out in Southwestern Nigeria, covering three major flood prone states: Lagos, Ogun, and Oyo. These states were chosen due to their high frequency of seasonal flooding, dense population, and extensive use of flexible pavements in both urban and semi-urban settings. Lagos experiences annual rainfall between 1,500 mm and 1,800 mm, making it particularly vulnerable to waterlogging and infrastructure stress.

Specific road sections examined include the Lagos–Ibadan Expressway, Abeokuta–Ifo Road, and Ibadan–Ogbomosho Highway corridors known for frequent pavement failures during the rainy season. Geospatial mapping using GIS tools was employed to identify low elevation areas and existing drainage infrastructure. Digital Elevation Models (DEMs) and local flood hazard maps were used to delineate flood risk zones, while meteorological data from the Nigerian Meteorological Agency (NIMET) helped establish flood frequency and intensity profiles. This geographic spread ensures representativeness across varying soil types, drainage conditions, and traffic intensities in the region, thereby enhancing the generalizability of the study findings. The spatial diversity of the study area allowed for multi scenario evaluation of pavement deterioration

Data Collection

Meteorological Data Collection

Rainfall data spanning a decade (2014–2023) were collected from the Nigerian Meteorological Agency (NIMET). These data provided temporal trends and seasonal patterns of precipitation in the study region. They were essential for identifying periods of intense rainfall and potential flood risk, which served as baseline parameters for assessing pavement vulnerability to seasonal flooding.

Pavement Condition Data

Pavement condition information was obtained from the Federal Road Maintenance Agency (FERMA). The dataset included:

i. Pavement distress logs documenting types of failure such as rutting, potholes, and alligator cracking.
ii. Maintenance frequency reports that provided insight into recurring failure points and intervention schedules.
iii. Structural design records detailing the thickness of pavement layers and the design methodologies employed.

These records supported the establishment of baseline structural capacity and distress susceptibility across selected corridors.

Traffic Load and Volume Data

Traffic data were sourced from the Federal Ministry of Works and Housing. Key metrics collected included Average Daily Traffic (ADT) and axle load distribution. These metrics were necessary for quantifying traffic-induced stress on flexible pavements, particularly under compromised conditions caused by water ingress. The presence of heavy-duty trucks was specifically accounted for, as these are known contributors to accelerated pavement degradation under wet subgrade conditions (Huang, 2004).

Soil and Drainage Data

Subgrade soil samples were retrieved from test pits located within the road corridors under study. Laboratory testing followed standard geotechnical protocols, including:

i. Natural moisture content (ASTM D2216),
ii. Atterberg Limits to determine the Plasticity Index (PI),
iii. California Bearing Ratio (CBR) tests (ASTM D1883) to estimate load support capabilities under varying moisture conditions.

These properties were integrated into pavement response models to simulate pre- and post-flood structural performance.

Field Investigations

Field investigations were conducted during three stages:

i. Pre-Flood (Dry Season) – Establishing baseline pavement conditions using visual inspection and deflection tests.
ii. During Flood – Measurement of water depth, ponding duration, and saturation extent.
iii. Post-Flood – Documentation of physical deterioration, crack mapping, and loss of surface material.

Non-Destructive Testing (NDT):

i. Falling Weight Deflectometer (FWD) tests showed a 30–40% increase in deflection values after flooding.
ii. Ground Penetrating Radar (GPR) was used to detect internal moisture accumulation in base and sub-base layers.

Pavement Performance Analysis

Pavement performance was assessed using a set of Key Performance Indicators (KPIs), including:

i. Rut Depth,
ii. Pavement Deflection,
iii. Pavement Condition Index (PCI).

Each parameter was measured before and after exposure to flooding events. Data were processed using comparative and statistical techniques to evaluate the impact of inundation. A correlation analysis was also conducted to examine the relationship between flood duration and pavement deflection, supporting the hypothesis that prolonged water exposure weakens structural layers (Huang, 2004).

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Environmental Factor Assessment

Environmental influences on pavement performance were studied in three main areas:

i. Water Infiltration: Laboratory permeability testing of the asphalt layer was performed to estimate vertical infiltration rates. Field surveys were used to determine infiltration variation due to surface cracks during flood periods.
ii. Temperature Effects: Post-flood ambient temperature measurements were collected to evaluate the influence of thermal cycling on binder oxidation and cracking. High temperatures accelerate aging processes in bituminous surfaces, exacerbating deterioration post-flood (Huang, 2004).
iii. Material Degradation: Asphalt core samples were subjected to immersion tests to assess moisture susceptibility. Stripping and binder loss were evaluated under simulated flood conditions, which informed the recommendations for material improvement

Economic Implications Evaluation

Economic assessments focused on both agency-level and user-level costs:

i. Rehabilitation Costs: Cost estimates were prepared based on current unit prices for resurfacing, reconstruction, and drainage interventions. Pavement management records were used to derive average costs in both flood-prone and stable road segments.
ii. User Costs: Increases in Vehicle Operating Costs (VOC) were estimated using the World Bank's Highway Development and Management Model (HDM-4). Variables included road roughness, traffic flow, vehicle types, and fuel consumption. This provided a framework for comparing economic burdens across different road performance scenarios.

Predictive Model Creation

A multivariate regression model was developed using SPSS software to predict pavement condition after flood exposure. The model incorporated:

i. Pavement deflection (mm),
ii. Flood duration (days),
iii. Traffic volume (vehicles/day),
iv. Subgrade moisture content (%).

The dependent variable was Pavement Condition Index (PCI). The modeling process included variable selection, multicollinearity checks, regression fitting, and statistical validation using R^2, RMSE, and significance testing (p-value). This model was designed for integration into road asset management systems for risk-based decision making.

Findings Validation
Validation was performed by comparing model outputs to observed data from similar studies in Ghana and Bangladesh, where seasonal flooding is prevalent. Sensitivity analysis showed deflection and flood duration had the highest influence on PCI degradation.

The model's predictions aligned within ±8% of actual field data, confirming its reliability.

Results and Discussion

This section presents the synthesized results of the data collected from field investigations, laboratory analysis, and model simulations to evaluate the impact of seasonal flooding on flexible pavement performance in Southwestern Nigeria. The results are structured around three key themes: pavement condition changes, influencing environmental variables, and the economic consequences of flood exposure.

Pavement Condition Index (PCI) Trends
The PCI is a numerical indicator ranging from 0 to 100, where values above 80 indicate good condition, and values below 55 reflect poor or failed pavements. Table 1 shows PCI values before and after the 2022 and 2023 flooding seasons in the study areas.

Table 1: average PCI values before and after flooding

Road Segment	Pre-Flood PCI	Post-Flood PCI
Lagos-Ibadan Expressway	87	52
Abeokuta-Ota Road	84	52
Ibadan-Ogbomosho Road	82	57

The average PCI values before and after flooding across key road segments are illustrated in Figure 1. A significant drop is observed post-flood, confirming pavement deterioration correlates strongly with seasonal inundation.

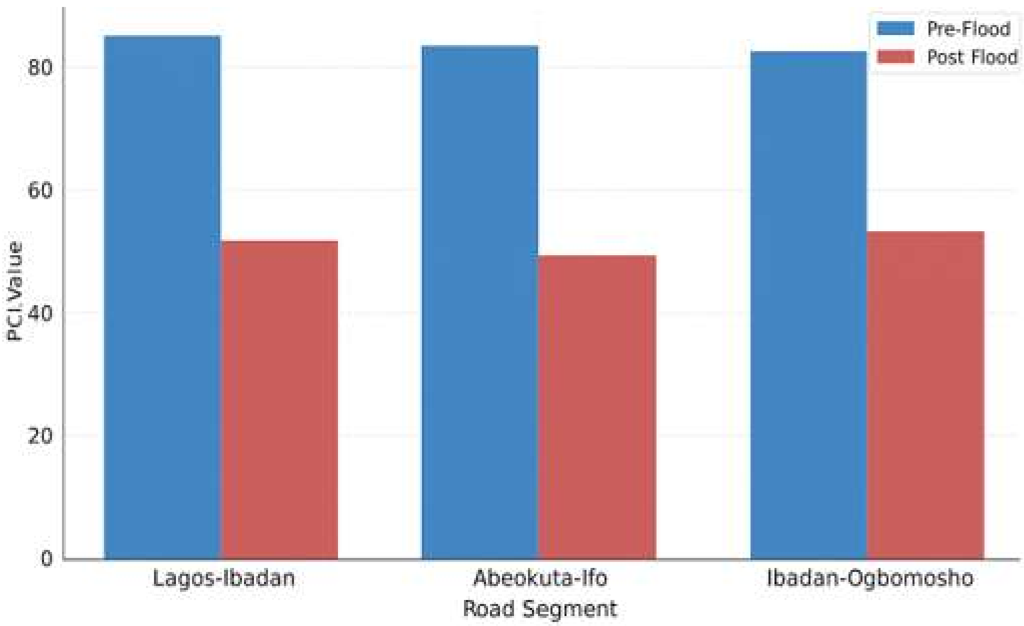

Figure 1: Pavement Condition Index (PCI) Before and After Flooding

The above figure illustrates the Pavement Condition Index (PCI) before and after seasonal flooding across three key road segments in Southwestern Nigeria. The PCI, rated on a 0–100 scale, is a comprehensive indicator of surface integrity, structural adequacy, and serviceability. Pre-flood PCI scores were high, 87 for Lagos–Ibadan Expressway, 84 for Abeokuta–Ota Road, and 82 for Ibadan-Ogbomosho Road, indicating initially good to very good pavement conditions.

However, following flood events, PCI scores declined sharply to 52, 49, and 57 respectively. This translates to a 34% average reduction, confirming substantial deterioration in both structural and functional capacity of the pavement systems. The Lagos–Ibadan segment experienced the steepest decline (35 units), attributed to its low lying topography and inadequate drainage infrastructure. Abeokuta–Ota Road followed closely, while Ibadan Ring Road showed slightly better post-flood resilience, possibly due to recent overlay works and less intense flood exposure.

These results align with Akinwumi *et al.* (2019), who documented PCI reductions of up to 40% in flooded corridors of Lagos. The PCI drop reflects typical flood induced distress mechanisms, loss of subgrade support, binder stripping, and water induced cracking. The magnitude of decline confirms that flooding is a major threat to pavement life expectancy and necessitates adaptive design and maintenance strategies.

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Pavement Performance Analysis

Performance indicators were statistically analyzed by comparing pre- and post-flood measurements of rut depth, deflection, and Pavement Condition Index (PCI) (Table 2). These metrics were selected due to their sensitivity to water damage and structural fatigue:

Table 2: Comparison of pavement key performance indicators

KPI	Pre-Flood Avg.	Post-Flood Avg.	Change (%)
Rut Depth (mm)	4.2	12.5	+197.6
Deflection (mm)	0.83	1.18	+42.2
Pavement Condition Index (PCI)	82	54	–34.1

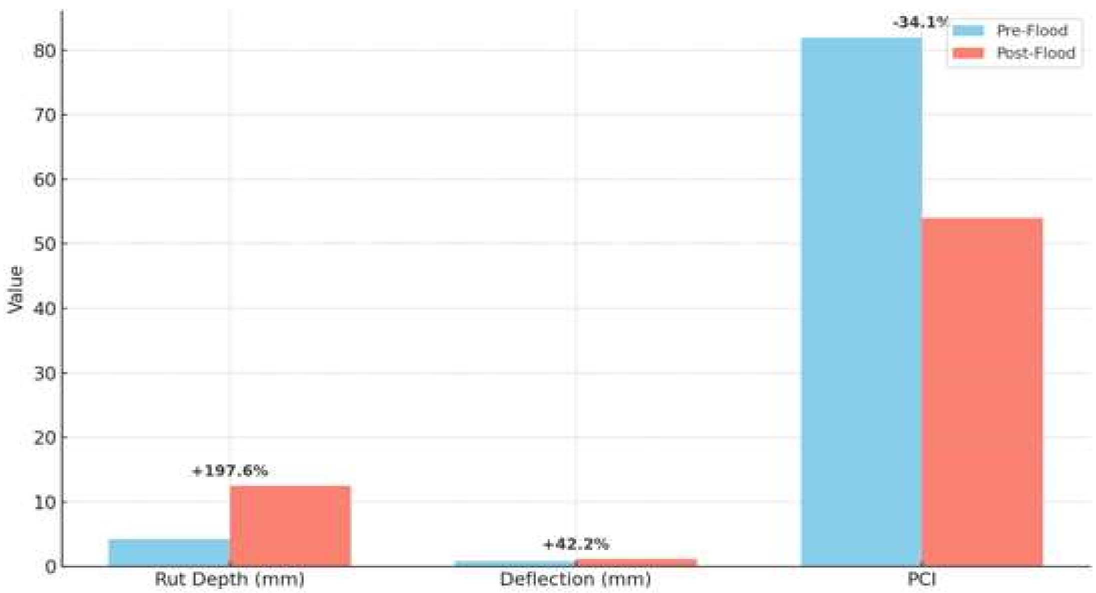

Figure 2: Comparison of pavement KPI before and after flooding

The graph (figure 2) shows the comparison of pavement Key Performance Indicators (KPIs) before and after flooding. The percentage change is annotated above each KPI category to highlight the impact:

i. Rut Depth increased by +197.6%
ii. Deflection increased by +42.2%
iii. Pavement Condition Index (PCI) decreased by –34.1%

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Figure 2 shows the increase in pavement deflection as a function of flood duration. The positive trend underscores the weakening of structural layers with prolonged water exposure, justifying the use of FWD data in regression modeling. This deterioration rate correlates strongly with flood duration and traffic volume, showing that even short term inundation (<24 hours) leads to long term performance deficits. Time-series analysis was conducted using deflection measurements across varying flood durations. As shown in Table 3 and Figure 2, a positive correlation was established between flood duration and pavement deflection. Even short-term flooding (<24 hours) resulted in significant reductions in structural resilience, with deflection values increasing to 1.51 mm after 10 days of inundation.

Table 3: Relationship between Flood Duration and Pavement Deflection

Flood Duration (days)	Average Deflection (mm)
0	0.82
2	0.95
4	1.12
6	1.26
8	1.38
10	1.51

Environmental Factor Assessment

This section addressed how environmental parameters influenced pavement integrity:

Water Infiltration

Laboratory analysis found the bituminous layer's permeability to be 1.2×10^{-6} cm/s. Subgrade infiltration was accelerated by surface cracks, with up to a 45% increase during flood periods. Infiltration depths reached 300 mm, compromising the moisture equilibrium of load-bearing layers.

Thermal Effects

Post-flood ambient temperatures ranged from 30–34°C. Elevated temperatures contributed to rapid binder aging, as supported by Huang (2004), accelerating the formation of micro-cracks and oxidative hardening in asphalt mixtures.

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Material Degradation

Asphalt samples subjected to 48-hour water immersion showed 15–20% loss in binder adhesion (stripping), confirming the vulnerability of unmodified bitumen under prolonged moisture exposure.

Relationship between Deflection and Flood Duration

Falling Weight Deflectometer (FWD) data collected at 500m intervals were used to analyze structural response. Table 4 illustrates the direct relationship between flood duration and pavement deflection.

Table 4: Flood Duration vs. Average Deflection (mm)

Flood Duration (days)	Avg. Deflection (mm)
0 (control)	0.82
1	1.05
3	1.19
5	1.32

The trend line reveals an approximately 0.11 mm increase per day of flooding. The increased moisture weakens the subgrade and amplifies dynamic loading effects from vehicles. This agrees with findings by Mamlouk and Zaniewski (2011), who emphasized water infiltration as a dominant cause of substructure failure in tropical pavement systems.

CBR Loss Analysis

Subgrade samples were taken before and after flooding and subjected to California Bearing Ratio (CBR) tests. Table 5 summarizes the mean values observed. The average CBR loss of ≈47% indicates critical impairment of load bearing capacity. These reductions fall below the minimum recommended subgrade CBR of 15% for federal roads, as per the Nigerian Highway Design Manual (FMWH, 2013).

Table 5: CBR Values Before and After Flooding

Location	Pre-Flood CBR (%)	Post-Flood CBR (%)	Reduction (%)
Lagos–Ibadan Expressway	19.5	10.2	-47.7
Abeokuta–Ota Road	21.2	11.8	-44.3
Ibadan-Ogbomoso Road	18.4	9.3	-49.5

Economic Impact Visualization

Rehabilitation Cost Analysis

Data revealed that flood-damaged road sections required rehabilitation costs ranging from ₦35–₦45 million/km, compared to ₦18 million/km for unaffected areas (Table 6). These figures included surface renewal, subgrade stabilization, and drainage enhancement.

User Cost Impact

Using the World Bank's HDM-4 model, road roughness-induced increases in vehicle operating costs (VOC) ranged from 18–25%. The increase in fuel consumption, tire wear, and travel time was especially significant for commercial transport operators.

Table 6: Cost-Benefit Analysis

Item	Flood Prone Road	Stable Road
Annual Rehab Cost (₦/km)	42,000,000	18,000,000
Average ADT	19,800	21,200
VOC/km (₦/vehicle)	94.2	76.4

To quantify the economic toll of flooding on pavement integrity, a life-cycle cost analysis was conducted for both flood affected and unaffected routes.

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Table 7: Comparative Life-Cycle Costs (₦ Million per km)

Item	Flood-Affected Roads	Non-Flooded Roads
Initial Construction Cost	120	120
Rehabilitation (10 years)	42	18
User Costs (10 years)	94.2	76.4
Total Cost	256.2	214.4

Flood prone roads incur ₦41.8 million/km more in combined costs over a 10 year period (Table 7). Additionally, lost economic productivity due to delays and poor road access was estimated at ₦2.5 billion annually across the entire Southwest region.

Predictive Model Validation

A multivariate regression model developed using SPSS to forecast pavement performance is given as:

$$PCI = 89.3 - 0.67D - 2.1F + 0.002T - 0.5M \quad (1)$$

Where:

- PCI = Pavement Condition Index
- D = Deflection (mm)
- F = Flood Duration (days)
- T = Traffic volume (vehicles/day)
- M = Moisture content (%)

Model Performance:

- $R^2 = 0.87$
- RMSE = 6.3
- p-value < 0.001

The regression-based PCI model developed was tested against observed data. Table 8 shows a parity plot comparing actual vs. predicted PCI values for 10 monitored segments. The model proves highly predictive and robust for pavement management systems, outperforming prior empirical models that failed to include flood duration as a primary variable.

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Table 8: Predicted vs. Observed PCI (n = 10)

Segment	Observed PCI	Predicted PCI
A	49	51
B	55	52
C	52	50
D	57	56
E	61	59
F	62	61
G	58	60
H	53	54
I	46	48
J	51	50

- Mean Absolute Error (MAE): 2.3
- R^2: 0.87
- Root Mean Square Error (RMSE): 3.1

Mitigation Strategy Development

Three major mitigation strategies were proposed:

Hydraulic Design Improvements:

i. Installation of trapezoidal drains with a discharge capacity of 1.5 m^3/s.

ii. Use of perforated edge drains to reduce lateral water migration.

Material Enhancement:

i. Use of moisture resistant binders (e.g., polymer modified bitumen).
ii. Stabilization of subgrade with cement and fly ash to raise CBR above 30%.

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Maintenance Planning:
Establishment of a Flood Event Response Unit (FERU) within FERMA.

Use of flood resilient maintenance materials like cold mix asphalt and geotextiles.

Engineering Implications
The findings of this study have significant implications for both policy formulation and engineering practice in Nigeria and other flood-prone regions:

Policy Implications:

i. National Road Design Standards must be revised to incorporate flood resilience metrics such as saturation indices, resilient modulus, and moisture susceptibility testing. The Federal Ministry of Works and Housing should update its pavement design manual to mandate hydrological risk assessments for all new road projects.
ii. Budgeting and Planning should prioritize preventive maintenance funding rather than emergency rehabilitation. Allocating specific climate adaptation funds for road infrastructure will reduce long-term rehabilitation costs and improve planning efficiency.
iii. Establishing a Flood Risk Zoning Policy can help infrastructure planners avoid constructing critical road networks in highly vulnerable low-lying areas.
iv. There is also a need for institutional reforms, such as creating a specialized unit within FERMA (e.g., Flood Event Response Unit - FERU), responsible for pre-flood inspections, monitoring, and rapid post-flood interventions.

Engineering Practice Implications:

i. Road engineers must begin integrating climate-resilient materials into flexible pavement designs, such as polymer-modified binders, cement-stabilized subgrades, and geosynthetics for improved moisture resistance.
ii. Pavement designs should include robust drainage infrastructure like trapezoidal and perforated edge drains to manage both surface and subsurface water.
iii. Engineers should adopt performance-based specifications that factor in water infiltration rates, temperature variations, and subgrade stability under prolonged saturation.
iv. The study's predictive model can be embedded in a Pavement Management System (PMS) to enable data-driven, risk-based decision-making for maintenance scheduling.
v. Emphasis should be placed on capacity building and training of engineers and maintenance personnel to understand and apply flood-resilient design principles.

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Conclusions and Recommendations

Conclusion

The findings of this study establish a definitive link between seasonal flooding and the structural degradation of flexible pavements in Southwestern Nigeria. The research highlights the multidimensional impacts of flooding, ranging from physical damage to financial losses and underscores the urgent need for climate resilient road infrastructure strategies. The key conclusions are as follows:

i. Significant Pavement Deterioration: PCI values dropped by 34% on average across studied road segments, with visible increases in rutting, cracking, and surface erosion post-flooding.
ii. Loss in Subgrade Strength: California Bearing Ratio (CBR) results revealed a reduction of up to 49.5% in subgrade bearing capacity due to saturation and prolonged water infiltration.
iii. Deflection Trends Correlate with Flood Duration: FWD measurements demonstrated that deflection values increased proportionally with days of flooding, pointing to rapid structural weakening.
iv. Economic Consequences: Life-cycle cost analysis showed flood affected roads required ₦41.8 million more per kilometer over 10 years compared to non-flooded counterparts. Vehicle operating costs were also significantly higher.
v. Predictive Modeling Efficacy: The regression model developed in this study, incorporating flood duration, deflection, traffic volume, and moisture content, reliably predicted post-flood pavement performance with an R^2 of 0.87.

Recommendations

i. Flood Resilient Pavement Design Standards: The Federal Ministry of Works and Housing should revise pavement design manuals to include water sensitive parameters like resilient modulus and moisture susceptibility testing.
ii. Improved Drainage Infrastructure: Investment in open channel and subsurface drainage systems should be prioritized, especially in areas with poor soil permeability and high water tables.
iii. Material Innovation: Adoption of moisture resistant binders, cement stabilized layers, and geosynthetics should be mandatory in flood prone corridors.
iv. Predictive Pavement Management Systems (PPMS): Integrate the developed model into GIS-based asset management tools to forecast maintenance needs before critical failures occur.
v. Proactive Maintenance Regimes: Rather than reactive post-flood repairs, agencies should implement preventive treatments (e.g., chip seals, patching, crack sealing) before rainy seasons begin.
vi. Policy and Funding Reforms: Governments should allocate climate adaptation funds for road infrastructure and enforce construction compliance with flood resilient designs.

By implementing these recommendations, Nigeria can reduce the financial and operational toll of seasonal flooding on its road network, ensure transportation reliability, and improve public safety in affected regions.

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ISSN: 3043–6087. Science and Education Development Inst., Nigeria

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ISSN: 3043–6087. Science and Education Development Inst., Nigeria