International Journal of Emerging Science and Engineering (IJESE)
ISSN: 2319–6378 (Online), Volume-14 Issue-4, March 2026

A Review of the Impact of Wheel Load on Flexible Pavement Under Submerged Conditions

Jaja Christine Israel, Jonah Agunwamba

***Abstract:** This paper presents a review of the impact of wheel load on the performance of flexible pavement under submerged conditions. Moisture ingress plays a major role in accelerating pavement failure. Flexible pavements represent a significant area of pavement engineering practice and research. Most pavements are flexible; they are supported by soil and have a flexible surface that can deform elastically under load. The review starts with the structural mechanics of flexible pavements, in which the behaviour of the different layers and the effects of wheel load distributions are discussed. It also explains how water seeps into the pavement and adversely affects its mechanical properties, leading to rutting, fatigue cracking, and material stripping. Analysing existing models, including analytical, finite element (FEM), and mechanistic-empirical, has emerged as the most effective for submerged pavement analysis, though each has limitations. However, incorporating climate resistance is crucial for predicting the performance of submerged pavement. A review of field and laboratory studies emphasises the necessity of obtaining empirical data to support model validation. In conclusion, it is important to incorporate measures to make pavements more moisture-resistant, adopt better modelling approaches, and address climate change. Future investigations should generate experimental data under submerged conditions and explore new materials and technologies to mitigate the effects of wheel load and moisture. This will help improve the performance of flexible pavements in waterlogged conditions.*

***Keywords:** Flexible Pavements, Wheel Load, Submerged Conditions, Water Infiltration, Pavement Performance, Rutting, Fatigue Cracking, Modelling Approaches.*

***Nomenclature**:*

FEM: Finite Element Modelling
AI: Artificial Intelligence
APT: Accelerated Pavement Testing
M-E: Mechanistic-Empirical
ML: Machine Learning
MEPDG: Mechanistic-Empirical Pavement Design Guide

I. INTRODUCTION

A. Background and Importance of the Study

Flexible pavements are a crucial part of today's transport system, designed to carry traffic loads safely without structural failure. They also remain structurally sound under varying levels of load and weather conditions. Modern engineering principles incorporate system reliability-based design to achieve this goal, as demonstrated by the use of adaptive meta-modelling to optimise pavement construction [1]. Water seeps into flexible pavements, affecting the subgrade and base and, consequently, weakening them, significantly reducing bearing capacity. The initial studies presented in the above paragraph recognise that water does cause damage. Still, they do not seem to consider the responses of different saturations, mix designs, and subgrades to long-term exposure [2]. As per [3], a statement indicating that the climate of some regions is changing and that drainage systems must be continually improved to avoid damage and deformation to road pavements is certainly a good one. As noted in [3], being underwater and having wheel loads have additional effects. This causes accelerated fatigue and structural damage. This provides valuable information but doesn't account for practical problems and is therefore quite limited. Existing mechanistic-empirical models are useful for understanding pavement behaviour [4]. Nonetheless, these models cannot reproduce hydrodynamic effects and do not account for the effects of repeated loading. Moreover, many studies use lab testing under idealised conditions that do not replicate the field. As a result, the applicability of their findings to field pavement design or rehabilitation is limited. Many existing models and experiments do not use advanced materials such as geosynthetics or modified binders [5]. This demonstrates a significant gap in research, namely the lack of sustainability considerations, such as the use of recycled materials to enhance water-damage performance. Not enough research is being done on the aspects of drainage efficiency and its measurable effects on pavement life, which limits the scope of studies at present, despite its importance being known. There is a need to adopt multi-disciplinary approaches (advanced simulations, field validation, novel materials) to improve pavement designs under these conditions. Utilising contemporary tools, such as machine learning, to increase the predictive capacity of water-pavement interaction models and allow for enriching pavement design codes with climate change effects for continuing functioning and durability of flexible pavements in water-rich climates.

Manuscript received on 29 November 2025 | First Revised Manuscript received on 20 January 2026 | Second Revised Manuscript received on 07 March 2026 | Manuscript Accepted on 15 March 2026 | Manuscript published on 30 March 2026.

*Correspondence Author(s)

Christine Israel Jaja*, Department of Civil Engineering, University of Nigeria, Nsukka, Enugu, Nigeria. Email ID: christine.jaja@yahoo.com, ORCID ID: 0009-0006-7739-3086

Prof. Jonah Agunwamba, Department of Civil Engineering, University of Nigeria, Nsukka, Enugu, Nigeria. Email ID: jonahagunwamba6@gmail.com

B. Problem Statement

Water infiltrating flexible roads causes many problems. It affects the pavement's strength and durability. When pavements are inundated with water or remain wet for a prolonged period, water enters thepavement layers, especially the subgrade and base, reducing load-bearing capacity and increasing vulnerability to damage. Water that gets into the flexible pavements causes weakening of the bonding between the aggregates and binder in bituminous layers, lower stiffness in the supporting layers, and the hastening of distress such as Rutting, Fatigue cracking, and stripping. These conditions not only impair the pavements' immediate performance but also drastically reduce their service life. The combined effects of wheel loads and water damage generate non-linear stress-strain relationships in both asphalt and concrete pavements that current pavement models do not adequately capture. Hence, there is a need to develop appropriate models for submerged conditions.

C. Objectives of the Review

To investigate the impact of wheel load on the mechanical behaviour of flexible pavements under submerged conditions, focusing on how water infiltration affects stress distribution, material properties, and pavement deformation.

To critically review existing models that simulate the interaction between wheel load and moisture in flexible pavements, identifying their strengths and limitations.

To propose potential improvements or novel approaches in modelling techniques that better account for the effects of submergence on pavement performance, including the integration of moisture-sensitive parameters and advanced computational methods.

D. Scope and Limitations

This review looks at the impact of water on flexible pavement performance. It studies the impact of water on a pavement's ability to resist wheel load. The review includes examination of analytical and numerical models for all of these cases. Despite being submerged, the flexible pavement can still perform its function. However, a rigid pavement will not behave this way. The discussion also excludes any other pavement failure mechanisms not associated with submergence.

II. MECHANICS OF FLEXIBLE PAVEMENT

A. Structure of Flexible Pavements

Flexible pavements are constructed with a multi-layer system that distributes traffic loads over time. Moreover, it also helps ease the hard structure of roads, ensuring the required behaviour. The basic function of every layer is to reduce stresses due to traffic, material properties, and layer properties. However, existing researchers have simplified the interaction to such a degree that complexity is overlooked, and thus they do not capture the load transfer mechanism across dissimilar materials. The bottom layer of the base and subgrade is generally natural soil or compacted material. The pavement system's performance depends on the subgrade layer. Even though [6] emphasises the importance of subgrade in providing a firm base for upper layers, the inherent variability of subgrade materials and the lack of standards to assess subgrade quality are insufficiently addressed. Also, a review [7] shows that waterlogged subgrades deform due to poor soil properties and improper compaction. Still, most analyses seem to ignore how subgrade properties interact with other parameters, such as drainage efficiency and changing moisture conditions, that affect system performance. Moreover, due to the above-mentioned reasons, there is often a lack of robust focus on how the interaction between subgrade deformation and upper layers can affect the long-term behaviour of pavements. The diagrammatic pavement layers, such as Figure 1, provide a theoretical basis but seldom integrate field responses and sophisticated simulations to corroborate in-field layered functioning. The need to adopt advanced materials in technology, such as soil stabilisation, has not yet been explored much in the subgrade context.

Another research gap is the effectiveness of geosynthetics and similar reinstatements in improving subgrade properties. From now on, a combination of experimental, numerical, and field data will assist in examining the more realistic models of load distribution and subgrade performance in field conditions.

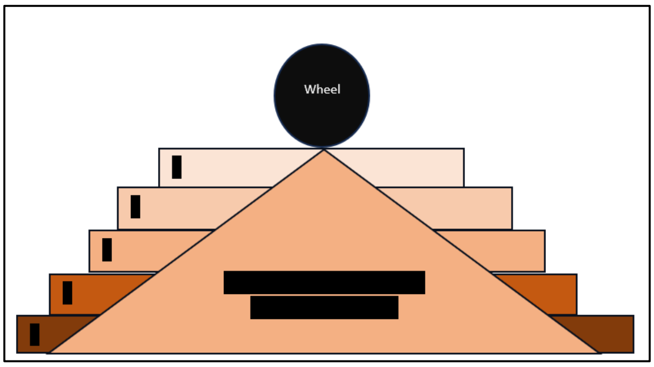
With the help of the latest analytical tools, researchers can recommend sustainable measures, such as recycled materials, optimised drainage design, and more, to achieve a stronger, more rugged, and more flexible pavement system.

[Fig.1: Typical Cross-sectional Structure of the Flexible Pavement]

Above the subgrade is the subbase. This consists of crushed stone or gravel. It serves an important purpose in load distribution and drainage. The authors of [8] argue for water build-up to be controlled to prevent structural weakening, but do not explore how the properties, compaction, and gradation of subbase materials can affect their performance under different conditions. The base course is made of better-quality aggregates, which give it strength by distributing stresses from the upper layers more uniformly on the subgrade or subbase. According to a recent publication, the choices made regarding the thickness and construction of the various layers are often overlooked. The topmost layer of a flexible pavement is the surface layer, which is a bituminous or asphaltic layer. This layer has to bear the direct loads and provide for the smooth movement of the vehicle. The nature and quality of the components – of the binder and materials (aggregates) – and related characteristics of this layer are significant determinants of its resistance to deformations, fatigue cracks, moisture stripping, etc. The appropriate characteristics of the reused bitumen (polymer, recovered bitumen) cannot be adequately specified by [9] through the material quality of the surface layer. Further, the layer thickness and shaping technologies used in construction affect aspects beyond impact performance. Bitumen is a binder that is also flexible and heat-resistant. However, its weakness to moisture penetration was noted. According to the research in [10], the study did not incorporate advanced modification methods, such as polymer modification or anti-stripping additives, that can reduce moisture susceptibility and increase adhesion. Just like rock mechanisation, the stiffness and durability of aggregates underpin the pavement's base and surface layers, helping it resist dynamic loading. However, research such as that of [11] does not appear to address the long-term performance of these materials in water, especially the impact of cyclic wetting and drying on cohesion and stiffness. Without adequate field studies or simulation models to address this, a significant void remains in understanding layer interactions in the pavement system. There should be a close consideration of material properties, interlayer interaction, environmental factors and so on in future studies. Also, new materials, more efficient construction methods, and sustainable approaches should be investigated to enhance the strength and durability of flexible pavements across diverse climatic and traffic conditions.

B. Wheel Load Impact on Pavement Structure

The wheel loads influence the distribution of stresses and strains in a flexible pavement system. Each layer can mitigate the stress or strain caused by vehicular loading [12]. The mechanism of load dispersion suggests that the intensity of stresses gradually dissipates with depth, as mentioned in [13]. This is true in case the pavement layers are properly designed and constructed. Nonetheless, [13] does not elaborate on how changes in material properties and actual axle loads, such as dynamic braking loads or uneven axle loads, disrupt the aforementioned load dissipation pattern. Assumptions about ideal conditions limit the practical relevance of these results to real traffic. In addition, while Emphasis by [14] has emphasised the input parameters, such as material properties, layer thickness, moisture conditions, etc., the interactions among these parameters under varying environmental field conditions, such as freeze-thaw cycles, were not taken into account. The paper written by [15] on mechanisms of load distribution suggests that every layer should have sufficient strength and stiffness to resist vertical stresses imposed by the wheel load. Nevertheless, the research does not assess the impact of more advanced materials, such as polymer-modified binders or geosynthetic reinforcements, on the mechanical properties of pavement layers [16]. This research identifies axle loads and tyre contact pressures as key factors affecting stress distribution. However, it does not account for the cumulative effect of repeated loading over time, which is important for understanding fatigue-induced degradation. The diagram in Figure 2 shows how loads are distributed in theory. However, no experimental work has been carried out recently. Similarly, it is not paired with heavy-duty 3D simulation tools to model the effects of traffic on shear stress and horizontal forces in pavement layers. Moreover, these studies are further limited in scope by the exclusion of tire-pavement interactions, such as slip and skid. Future research must provide innovative solutions to address complex analysis of wheel loads, pavement structural response, and material properties, the incorporation of sustainable materials, and the tire-pavement interaction phenomena, which are often overlooked in these studies. The future scope of using smart materials, innovative monitoring systems, and machine-learning-based predictive models could help advance our understanding of stress-strain behaviour in flexible pavements and inform design.



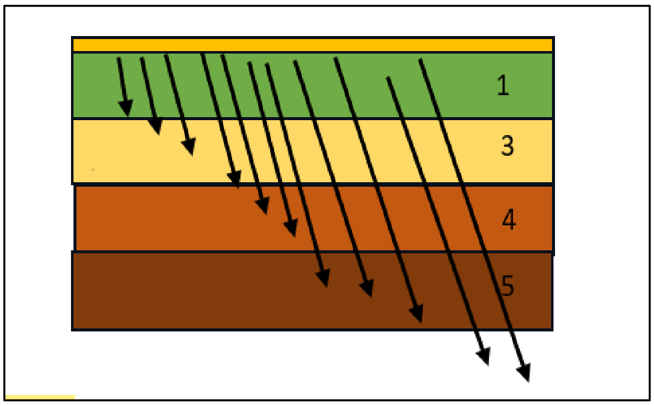
[Fig.2: Typical Wheel Load Distribution in a Flexible Pavement]

Besides axle load and contact pressure, the configuration of the tyre—such as tyre size, inflation pressure and number of axles—affects the distribution of wheel loads. For instance, dual tyres spread the load over a wide area, putting less stress on the pavement than single tyres [17]. The interaction of these parameters will determine the pavement layer's stress and strain. When submerged, the pavement can no longer spread the load, as water infiltrates the materials and breaks the bond between them, especially between the base and subgrade. The layers which are saturated with water will have poor strength and will deform and fail under repeated loading. This underscores the need for a robust design and appropriate material selection in flexible pavements under wet wheel loads [18].

III. INFLUENCE OF SUBMERGENCE ON PAVEMENT PERFORMANCE

A. Water Infiltration and its Effects

When water enters the pavement, it causes the materials to behave differently and lose their strength through physical and chemical processes [19]. When water seeps into spaces within overflow areas, it generates hydraulic pressures that weaken bonds between different materials. In the analysis as per [20], pore pressure-induced deformations under traffic loading are effectively highlighted. Still, various aggregate types or degrees of compaction do not affect pavement performance, and this is not adequately addressed. According to [21], capillary rise and moisture migration from subgrade to upper layers occur more readily in finer soils. However, [21] does not assess how different soil stabilisation techniques, like the use of lime or cement, can reduce capillary rise and enhance resilience. An important factor affecting the rate and extent of water movement in the pavement system is the material's permeability [22]. Although [22] propagates the idea that high-permeability material makes water flow faster and saturate the subgrade, it makes no mention of using a drainage layer or adding a hydrophobic additive to the bituminous mix to prevent this from occurring. As shown in Fig. 3, water infiltrates through the pavement layers, indicated by the downward-pointing arrows. However, the figure does not show which parameter affects this infiltration, such as rainfall intensity or movement. Moreover, ongoing research does not address the interaction between infiltration pathways and effects such as thermal regimes and freeze-thaw cycles, which produce cracking and swelling of water. Future studies should aim to conduct research at multiple scales, including material properties, environmental conditions, and traffic conditions. More advanced options, such as nano-modified materials or enhanced drainage designs, should also be considered to reduce water infiltration and its decomposition.



[Fig.3: Typical Process of Infiltration of Water into Subgrade]

When water enters the pavement structure, it materialises. 3 properties are greatly affected, and the pavement material's capacity to bear traffic stresses is fundamentally changed. The drag force of the heavy vehicles can be significantly increased due to the water ponding on the road surface. The water physically exerts a drag force on the vehicle, causing the engine and braking system to consume more fuel. Although [23] clarifies stripping and its effects, it makes no mention of anti-stripping agents or polymers that mitigate the issue and improve the binding between the binder and aggregates, thereby prolonging pavement life. As mentioned above, the loss of adhesion in the bituminous binder will compromise load-carrying capacity. Thus, the surface would easily deform under repeated wheel loads. However, this statement doesn't mention that tests such as the moisture susceptibility test are essential for quantifying and predicting stripping under different environmental conditions and across different materials. When the subgrade becomes saturated with water, its shear strength drops sharply, whereas its compressibility increases markedly. Generally, soils rich in clay are more susceptible to deformations and differential settlement. Also, [24] states that when unsafe levels of water saturation happen, the capacity of subgrade soils is affected by destabilisation.

However, the analysis does not consider the joint effects of traffic loading and water infiltration, e.g., dynamic pore pressures or freezing-thawing damage. Also, these studies do not examine the use of permeable pavements and the addition of geotextiles to enhance thick pavements for drainage. Research needs to move towards a more holistic approach that incorporates, amongst others, materials science, hydrology, and traffic engineering related to water damage. New technologies, such as wireless sensors to monitor soil water levels and AI tools to predict damage, can significantly reduce water damage to pavement performance and durability.

B. Submergence and Pavement Deterioration

Extended exposure to water can have diverse effects on flexible pavement, causing damage such as rutting, fatigue cracking, stripping, and failure of the lower pavement layers. Water damage accelerates these mechanisms. The occurrence of Rutting or permanent deformations in the wheel path is aggravated when submerged, as it weakens the subgrade and base layers [25]. According to [25], water causes this reduction in resistance to deformation, but it doesn't address the material modifications or stabilisation mechanisms to prevent rutting under these conditions. Water-saturated soils' tendency to 'displace' under repeated loading [26] plays a critical role in rut formation, which first increases vehicle fuel consumption and second makes the road unsafe. But the interaction between soil type, water content, and load intensity is not specifically analysed, which is important for targeted intervention. Stripping occurs when water damages the bond between bitumen and aggregate in bituminous layers, affecting the structural integrity of these layers (ravelling, potholes, etc.) [27]. The source [27] appropriately discusses the impact of stripping, but fails to mention preventive measures such as anti-stripping additives, polymers, and adhesion-improving treatments used to improve pavement performance. Moreover, [28] states that fine particles are dislocated by hydraulic action under traffic loads in the lower layers. Fine grains are displaced, which causes weak pavement subgrade and uneven settlement. However, [28] does not review the assessment of the use of geosynthetics, improved drainage systems, or alternative base materials to mitigate these effects. The authors agreed that submergence is an important factor in pavement performance. But none of them provides a unifying study that explores the role of traffic speed stress, material stress, and environmental factors. There is an important need for researchers to formulate improved modelling techniques to assess the dynamic water-pavement interactions and real-time monitoring to ensure pavements are designed for long-duration water. Furthermore, the main focus of mitigation efforts should be the use of innovative materials, improved drainage strategies and lifecycle cost analyses.

Table I: Impact of Submergence on Flexible Pavement Deterioration

Deterioration Aspect	Description	Effect	Reference
Rutting	Deformation in wheel paths under load worsens in waterlogged soils.	Increased fuel use, safety risks	[26][27]
Fatigue Cracking	Cracks form in saturated layers due to reduced stiffness under repeated loads.	Water infiltration, weakening	[28]
Stripping	Water weakens the bond between bitumen and aggregate, reducing layer strength.	Ravelling, potholes	[29]
Hydraulic Action	Traffic-induced water movement displaces subgrade particles, eroding the foundation.	Uneven settlement, deformation	[30]
Overall Submergence	Prolonged water exposure accelerates deterioration, impacting pavement lifespan.	Need for advanced design	[26][27][28][29][30]

IV. MODELLING APPROACHES FOR WHEEL LOAD AND PAVEMENT RESPONSE

A. Analytical Methods

Burmister’s two-layer theory primarily involves an analytical model in which the flexible pavement's stress and strain responses to wheel loads are estimated based on the elastic properties of its top layer and subgrade. These models calculate stresses, strains, and deflections. They make it easy to model pavement behaviour. However, as pointed out in [29], the derived analysis from these models is useful. Still, the drawbacks stem from the assumptions made in the models, which are: (1) Homogeneity of the material: constant mechanical properties, (2) the materials are isotropic: mechanical properties are independent of direction, and (3) Linear elastic behaviour: stress proportional to strain. These do not reflect pavement reality. The water application scenarios may not apply to these models as they were developed for dry conditions [30]. According to [30], initial analyses of pavements can use analytical solutions. This research, however, fails to make a strong case for their inability to capture the evolving, non-linear material responses to water infiltration, which move away from reality.

According to [30], in submerged conditions where water ingress would alter the mechanical behaviour of pavement materials, the performance of analytical models would be unreliable. According to [31], saturation effects render the responses of the subgrade and base layers non-linear and time-dependent, which are not captured by classical theories such as Burmister's. Although the limitations identified in [31] are acknowledged, it does not propose any modifications to the methods, nor does it consider additional aspects such as pore-water pressure, changes in permeability, or moisture-induced softening in predictions. This is because they do not predict the behaviour of the structures under severe conditions.

The absence of transient behaviour, such as moisture movement and its repetitive action under cyclic loading, casts doubt on the legitimacy of analytical methods in underwater conditions [32]. As cited in [32], it is obligatory to apply a superior modelling technique (either numerical or hybrid). Still, it does not specify how this can overcome the shortcomings of an analytical model. Ultimately, we can understand how conventional analytical models can capture the basic behaviour of a pavement. Still, the limitations of these models also underscore the need for advanced multifunctional modelling to capture water-pavement interventions. Future research must shift towards mechanistic-empirical approaches or finite element models that incorporate field variability and relevant water parameters, including hydraulic permeability, pore-water pressure, and progressive material deterioration. As a result, pavement design and management may be conducted wisely under submerged conditions using advanced modelling approaches.

B. Finite Element Modelling (FEM)

FEM modelling is a good advance for simulating flexible pavements under water. The wheel load and pavement interface were simulated using high-detail finite element analysis. FEM breaks the pavement structure into smaller elements with specific material properties and provides a precise analysis of the material's moisture-induced non-linear and time-dependent behaviour, unlike conventional analytical models [33]. FEM can account for hydrological effects, such as pore-pressure weakening from infiltration, and use them to assess a submerged pavement case. Several studies, such as [34], elaborate on how, in FEM, the mechanical and hydrological interactions are modelled to assess stress redistribution, deformation mechanisms, failure mechanisms, etc. But these studies usually do not highlight the computational demands and the need for precise materials, limiting their application in less-controlled situations. One of the key strengths of the Finite Element Method is its ability to provide highly accurate simulations of real-world boundary conditions, such as water flow, drainage efficiency, and loads.

FEM design can render the design check for pavements built on soft soils obsolete. For example, case studies in [35] demonstrate how to use FEM to predict rutting and cracking under high axle loadings in waterlogged regions. The sub-grades weaken, and the base becomes less stiff. Many studies have validated the above, but there is a gap in the literature on the sensitivity of FEM output to input changes and to uncertainties arising from changes in various parameters, such as soil or material properties, under submerged conditions. In addition, the literature does not elaborate much on the computational intensity of the FEM, particularly for bigger or longer analyses.

In addition, FEM can forecast pavement damage in submerged conditions, including rutting and cracking, as satisfactorily demonstrated by [36]. However, it could have gone more in-depth into hybrid modelling techniques. If field validation is challenging, the combination of models like (FEM) can increase prediction accuracy.

Retrieval Number:100.1/ijese.A263414011225
DOI:10.35940/ijese.A2634.14040326
Journal Website: www.ijese.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

Moreover, new investigations suggest that FEM can be implemented at the regional or network level for pavements. The finite element method’s ability to incorporate sophisticated material behaviour and environmental interactions is evidence of its power, even given its limitations and the phenomena it cannot capture. Future advancements should focus on enhancing the computational efficiency of FEM, improving material characterisation techniques, and implementing a predictive mechanism for assessing the long-term performance of pavements under varying climatic and loading conditions.

C. Mechanistic-Empirical Models

M-E models can describe the pavement's behaviour under moisture. M-E models merge mechanistic equations—the evaluation of the effect of wheel loads on pavements using the theory of elasticity —with empirical data—measurements from field/laboratory tests — to predict pavements under field submerged conditions more realistically. Models for materials include moisture-related parameters, which are moisture content, saturation, and permeability, which lead to the assessment of the behaviour of materials due to water in terms of strength, stiffness, and deformation under wheel loads [37]. The combined strategy provides a superior understanding of pavement behaviour compared with classical models that disregard moisture. M-E models can perform actions that change material properties due to moisture, improving the accuracy of predicting what will happen to the pavement when it is submerged. Environmental factors such as water infiltration and drainage efficiency are incorporated into these models to enable accurate performance assessment. These models fit well in pavement design and management systems [38]. M-E models of structural behaviour are used to take care of changes in the properties of the material because of moisture. This leads to improved prediction accuracy for pavement life and the failure mechanism of submerged pavement. Moreover, by applying the M-E model to the pavement design and management system, they can improve water infiltration and drainage efficiency [38]. These models can continuously simulate the interaction of water, soil, and pavement materials. As a result, they help maintain the pavements in regions susceptible to water damage, such as those with heavy rainfall or poor drainage. Upon close inspection of the existing models, it has been observed that the models differ in efficiency, especially for various submerged-condition failures. Pavement performance evaluation for models calibrated for moisture sensitivity, such as the AASHTO MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE (MEPDG), has been very useful [39]. While these models are robust, there are still opportunities to improve their representation of dynamic water-flow patterns under extreme weather/drainage conditions. It is suggested that improving water efficiency under dynamic conditions will enhance the reliability of structural design models. Besides, M-E models have several advantages over both mechanistic and empirical models. However, the original research also requires high-quality field data. Table II shows different models and their pros & cons, as well as the reference used to study pavement response to wheel load under submerged conditions.

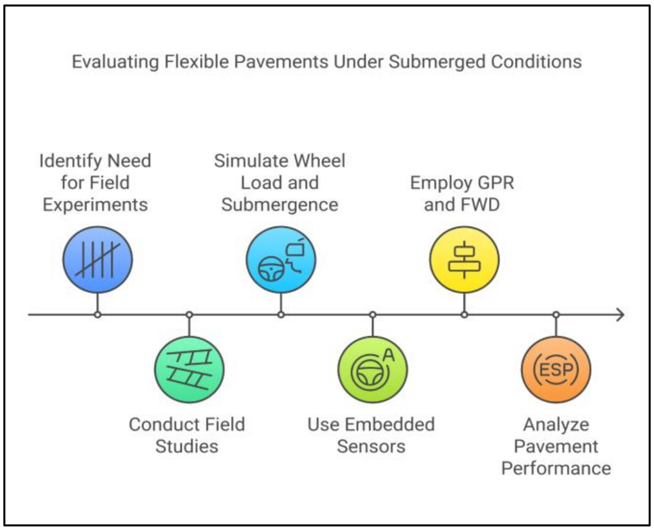
Table II: Summary of Modelling Approaches for Pavement Response to Wheel Load

Modeling Approach	Description	Advantages	Limitations	References
Analytical Methods	Traditional models, such as Burmister's theory, estimate stress/strain under dry conditions.	Simple, foundational understanding	Limited to ideal, dry conditions, assumes linear elasticity	[29], [30], [31], [32]
Finite Element Modelling (FEM)	Discretizes pavement system for detailed analysis under complex, submerged conditions.	Captures non-linear, real-world moisture effects	Computationally intensive, requires specific software	[33], [34], [35], [36]
Mechanistic-Empirical (M-E)	Combines mechanics with empirical data, factoring in the impact of moisture on materials.	Realistic predictions for submerged conditions	Some models lack dynamic water flow integration	[37], [38], [39]

V. EXPERIMENTAL STUDIES ON PAVEMENT PERFORMANCE UNDER SUBMERGED CONDITIONS

A. Field Experiments

Water testing flexible pavements in a field experiment helps understand the performance through observations [40]. Testing flexible pavements in drainage. Many field studies have been conducted to assess the impact of water on pavement damage, especially in flooded or poorly drained areas [41], and to conduct repeated Water Infiltration Experiments. Resilient pavements are seriously distressed due to instability. Pavements undergo severe damage when water enters the mix, causing instability. Many field studies have been conducted to determine the influence of water on pavement damage, especially in flooded or poorly drained areas. Instability causes severe pavement distress in resilient pavements. A few researchers monitored field experiments and observed changes in water-table fluctuations. Studies on highways subject to flooding have shown that their service life is considerably reduced due to increased moisture in the subgrade and base, which causes enhanced fatigue and structural failures [42]. To mimic waterlogging in field experiments, flooding conditions are often simulated by applying wheel loads and submergence. The pavement layers contained sensors to measure moisture, pore pressure, strain, and deformation, which helped researchers assess the pavement's response to wheel loads and submerged conditions. Researchers also combine GPR and FWD technologies in field studies to assess pavement structure and deterioration under submerged conditions [43]. Flexible pavements are monitored under submerged conditions, as shown in Fig. 4. Moreover, the above method emphasises the importance of conducting field experiments to simulate wheel loads and submergence, incorporating sensors for data collection and using GPR and FWD for pavement maintenance.



[Fig.4: Process for Evaluating Flexible Pavements Under Submerged Conditions]

B. Laboratory Investigations

Along with field tests, laboratory studies provide facilities in controlled environments to systematically investigate the effects of wheel loads and water on pavement performance. In laboratory conditions, researchers can easily replicate field conditions using accelerated pavement testing (APT) and moisture conditioning to study submerged pavements under traffic and environmental loads [44]. Setups that APT replicates years of use in a short time, thereby providing good data on the deterioration rate during submergence. Scientists can change the level of wetness and simulate various levels of submergence in an APT test, which helps in understanding the effect of water on each layer [45].

One of the most popular techniques in experimental settings is the conditioning of samples by moisture. In this method, pavement samples are presented with cycles of wetting and drying. In other words, samples are submerged and drained. This simulates the effect of submersion and subsequent drainage in the field [45]. After being created, these samples are subjected to various loads to determine the effects of water on their strength, stiffness, and durability. The laboratory work usually shows performance that is considerably worse as the moisture content rises, making the material more susceptible to rutting and cracking. These findings help us create moisture-resistant materials and better pavement designs for wet areas.

A crucial element of laboratory-based studies is the use of wheel-load simulation devices, such as wheel-tracking machines, which apply repeated wheel loads to asphalt/pavement specimens under controlled moisture conditions. These machines simulate tyre loads on submerged pavements and measure deformation, strain, and failure at a fixed point in time [46]. The implementation of wheel tracking devices has proven beneficial in recognising how submerged conditions hasten distresses like rutting and fatigue cracking, primarily due to high axle loads. In conclusion, laboratory studies generate useful data to support theoretical models and enhance design criteria for submerged pavements [47].

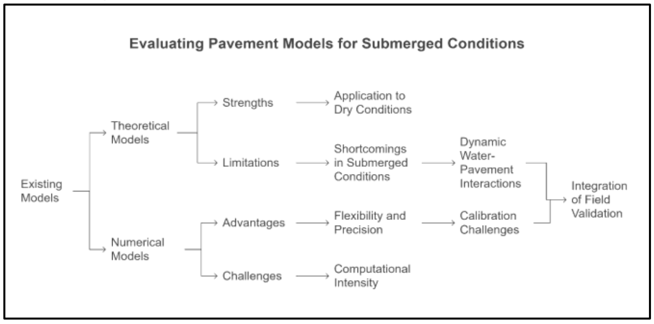
VI. CRITICAL EVALUATION OF EXISTING MODELS

A. Strengths and Limitations

Currently, performance prediction models of flexible pavements under inundation conditions have made significant progress in advancing the understanding of pavement behaviour. Still, they have certain strengths and weaknesses that warrant a critical evaluation. Models based on theory and analysis (layered elastic theories) and stress-strain equations (such as Burmister's theory) remain the focus of pavement analysis, particularly for dry conditions where material properties remain essentially unchanged. These models are appreciated for their simplicity and computational efficiency, making them suitable for the preliminary design stage and for simple structural designs [48]. Using these for submerged conditions has many demerits. Specifically, these models assume type homogeneity and linear elasticity, which is insufficient to represent the complex, non-linear and time-dependent behaviour of pavement material under moisture. When submerged, additional mechanisms can destroy the material, including pore-pressure buildup and material weakening. As a result, it doesn't include dynamic water-pavement interactions, which are essential for predicting pavements' long-term performance under repeated traffic loading in wet conditions [49]. Analyses that undergo extensive loading or have poor drainage capacity are often destroyed. This is likely the case with most analysis models, wherein there will be gaps.

Unlike analytical models, numerical models, especially FEM (Finite Element Models), are a great advancement because they can account for non-linear material properties, varying moisture conditions, and complex boundary interactions [50]. The FEM technique is useful in modelling the combined effects of wheel loads and moisture infiltration on pavement layers' stresses, deformations, and failures. This is important when submerged pavements are analysed, as moisture at the interface of the pavement with soil can be highly complex and non-linear. Although more flexible and accurate than analytical methods, they pose significant implementation challenges. The high computational demand of FEM is a well-known disadvantage. It requires substantial resources and time, especially for simulating the long-term performance of large pavements or several traffic cycles. The accuracy of FEM predictions also relies heavily on the precise calibration of material properties and boundary conditions, which can be challenging for heterogeneous materials or for unpredictable water movements. Uncertainties related to the difficulty of obtaining accurate material data (particularly in situ) make the model less applicable. FEM, while better suited to simulate moisture effects than earlier methods, relies on accurate input data and extensive site validation, especially for complex subgrade properties and changes in moisture infiltration patterns [51].

Thus, while FEM greatly enhances the capability to model submerged pavements, it is imperative to address the stated uncertainties and calibration issues. In conclusion, both analytical and FEM models have their own shortcomings that lead to significant uncertainty and inaccuracy in modelling submerged pavements and hence require validation from field data [50][51]. Ongoing field validation and improvements to these models are critical to enhancing the state of knowledge concerning these submerged pavements. Fig. 6 shows an organised ranking of pavement models used in submerged conditions, including theoretical and numerical models. Theoretical models may be applicable in dry situations; however, they have disadvantages in submerged situations due to the dynamic water-pavement interaction, which requires field validation. The numerical models are flexible and can yield precise results. However, the computational intensity and calibration difficulty are hurdles. Also, integration of field data along with numerical models was required.

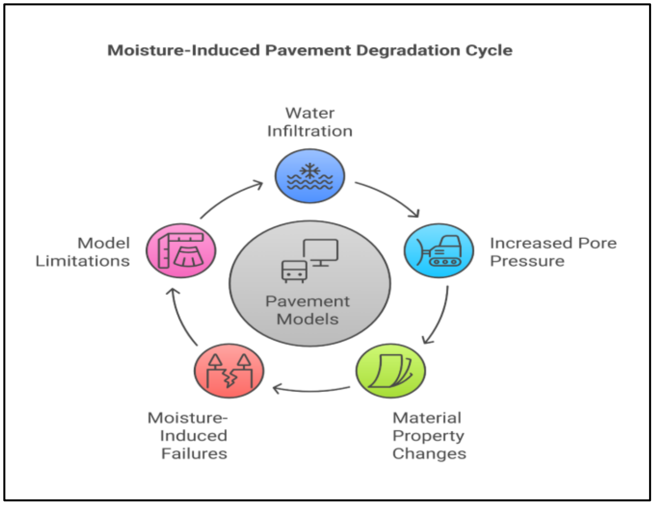


[Fig.5: Evaluation of Pavement Models for Submerged Conditions]

B. Incorporation of Moisture Effects

A major difficulty with existing pavement models is incorporating moisture effects. Specifically, submerged conditions can change material properties such as stiffness, cohesion, and load-bearing capacity. Many current models assume that materials can be treated a certain way, but this is not the case when water penetrates the pavement. Various failures occur in pavements due to water within them (saturation). For instance, subgrade soils, under saturated conditions, may lose a significant portion of their load-bearing capacity. This will severely weaken the foundation. On the other hand, the bituminous layer often undergoes stripping and loss of cohesion. These phenomena are critical for the durability of pavements. Moisture-related effects are often only partially implemented in mechanistic-empirical (M-E) models by employing empirical adjustments to mimic moisture change. Mechanistic-empirical (M-E) models can be reasonably accurate when based on field and laboratory data. Still, the main criticism levelled against them is that they cannot capture the evolving, real-time relationship between wheel loads and moisture-damage mechanisms [52]. M-E models simplify the complex interaction between wheel loads and the moisture-damage process by modelling damage progression in response to moisture variations over time, rather than an instantaneous event, which leads to pavement failure under flooding.

On the other hand, an important inadequacy of the current models is the absence of hydrostatic pressure and its effect on the overlay. When water enters the soil, the soil's pressure goes up. This rise in pressure makes the soil more likely to bend and break under the weight of things like cars and trucks. Furthermore, this factor is essential for developing and predicting failure mechanisms that lead to rutting, stripping, and cracking, particularly under high wheel loads in wet conditions. Many models underestimate or ignore the role of hydraulic pressure, thereby hindering their ability to accurately predict how water enters and interacts with the pavement system. The models are unreliable because they do not capture how moisture accumulates progressively in the pavement layers over time and how it affects material properties and deformation. Current models fail to account for time-dependent features, including moisture-related failures that occur after repetitive loading cycles, leading to poor prediction of long-term performance, notably in flood-intense or wet environments [53]. The cycle of wetting and drying of pavements causes their deterioration, as shown in Figure 6. The process begins with water penetration, raising pore pressure in the pavement. Thus, the material's properties change. All these changes make the pavement structure more susceptible to moisture-induced failures, such as cracking and deformation. The cycle ends with model limitations that highlight difficulties in precisely predicting and managing moisture-related pavement damage. This loop of feedback shows the necessity of better pavement models for dynamic water-pavement interactions.



[Fig.6: Moisture-Induced Pavement Degradation Cycle]

In summary, while existing models offer valuable frameworks for understanding pavement behaviour, their inability to fully incorporate moisture-related effects—such as hydrostatic pressure, material degradation, and progressive damage—remains a major shortcoming. The incorporation of more advanced modelling techniques that integrate moisture-flow dynamics, material degradation processes, and time-dependent factors is essential for accurately predicting flexible pavement performance under submerged conditions. Future advancements in this area should focus on refining these models better to capture the complex, evolving nature of moisture-pavement interactions and to enhance predictive capabilities for real-world scenarios where moisture plays a critical role in pavement deterioration [54].

Table III: Critical Evaluation of Pavement Models Under Submerged Conditions

Aspect	Analytical Models	FEM Models	M-E Models	References
Strengths	Effective for dry, basic conditions; low computation	Handles complex interactions; models moisture effects	Combines equations with field data; adjusts for moisture	[48][49][50]
Limits	Assumes linear elasticity; misses moisture-related damage	High computation; needs accurate data and calibration	Limited in dynamic load-moisture effects and time factors	[49][51][52]
Moisture Effects	Simplifies water-pavement effects, missing pore pressure impacts	Models coupled load-moisture effects, but data-dependent	Uses empirical data but lacks hydrostatic pressure details	[52][53][54]
Key Gaps	Misses' submersion and progressive water damage	Inaccuracies in material responses to water	Limited on pressure effects, gradual moisture buildup	[55][56][57]
Advancement Needs	Add dynamic moisture and degradation effects	Improve data accuracy and water modelling	Enhance moisture, load, and material degradation modelling	[59]

VII. POTENTIAL IMPROVEMENTS AND FUTURE DIRECTIONS

A. Integration of Advanced Techniques

One key area for improving the modelling of wheel-load impact on flexible pavements under submerged conditions is the **integration of multi-phase flow models**. Traditional models often simplify water infiltration and its effects on pavement layers. Still, multi-phase flow models have the potential to more accurately simulate the interactions among water, air, and solid materials within pavement structures [55]. By representing water as a distinct phase with its own flow dynamics, these models can more accurately capture the behaviour of moisture as it infiltrates the pavement layers, builds pore pressure, and influences material properties. This approach would allow for a more precise analysis of how water redistributes wheel loads across different layers and contributes to accelerated deterioration under submerged conditions [55].

Furthermore, the incorporation of **artificial intelligence (AI) and machine learning (ML)** models presents a promising frontier in pavement research. AI algorithms can learn from vast datasets of pavement performance under various loading and environmental conditions, enabling the prediction of complex behaviours that traditional models struggle to capture. Machine learning models, in particular, can be trained on historical data from field and laboratory studies to predict pavement responses under submerged conditions, accounting for factors such as wheel load, material type, moisture content, and submergence duration. These models can also be updated in real time as new data becomes available, making them dynamic tools for assessing pavement health and predicting failure risks [56].

B. Consideration of Climate Change Impacts

Another critical consideration for future pavement modelling is the **impact of climate change**, which is expected to intensify the challenges posed by submerged conditions. **Increased rainfall, rising water tables, and more frequent flooding events** will exacerbate water infiltration into pavement layers, leading to greater stress and faster deterioration. As a result, pavement design and maintenance practices must evolve to account for these future environmental conditions. This calls for the development of climate-resilient pavements that can withstand prolonged exposure to water, as well as models that incorporate **climate change projections** to predict how flexible pavements will perform under increasingly extreme weather events [57].

The need to consider new materials and construction techniques that improve drainage, enhance material durability under wet conditions, and reduce the vulnerability of subgrade and base **layers** to saturation. Additionally, maintenance schedules may need to be adjusted to account for the accelerating effects of climate change, with more frequent inspections and repairs required in regions where flooding and waterlogging are likely to become more common [57].

C. Development of More Accurate Submerged Pavement Models

To address the limitations of existing models, there is a need to develop **more accurate models** that integrate real-time field data with **advanced computational simulations [58]**. By coupling field monitoring technologies, such as sensors that measure moisture content, pore pressure, and pavement deflections, with sophisticated computational tools, such as finite element modelling (FEM) and multi-phase flow analysis, researchers can create models that are not only more predictive but also adaptive to changing conditions. This real-time feedback loop between field data and modelling would allow for more precise predictions of pavement performance under submerged conditions and enable timely maintenance interventions before significant damage occurs [59].

Moreover, these models should account for the full range of **moisture-related effects**, including hydrostatic pressure, capillary action, and the time-dependent accumulation of moisture in pavement layers. Advanced models could incorporate **stochastic elements** to simulate the random nature of water infiltration and its uneven distribution across pavement surfaces, thereby further improving prediction accuracy [60].

VIII. COMPARATIVE ANALYSIS OF GAPS, LIMITATIONS, AND APPROACHES IN PAVEMENT MODELLING RESEARCH

Modelling flexible pavements under submerged conditions presents a multifaceted challenge, stemming from the interplay among environmental, material, and mechanical factors, despite advancements across various modelling paradigms. Key limitations and gaps persist, hindering accurate prediction of pavement behaviour. This comparative analysis evaluates these deficiencies across analytical, mechanistic-empirical (M-E), numerical, and advanced computational approaches, and discusses emerging strategies to address them.

A. Analytical Models

Analytical models, grounded in classical theories like the layered elastic approach, provide a foundational framework for pavement analysis. These models offer computational simplicity and facilitate initial assessments of stress-strain distributions under wheel loads. However, they rely heavily on idealised assumptions, such as material homogeneity and linear elasticity, which fail to capture the complexities introduced by moisture infiltration and hydrostatic pressures under submerged conditions. For instance, analytical models overlook the non-linear deformation characteristics of water-saturated subgrade soils and the weakening effects on asphalt layers caused by moisture-induced stripping. Consequently, while these models are useful for preliminary designs, their applicability is limited in dynamic or moisture-sensitive scenarios.

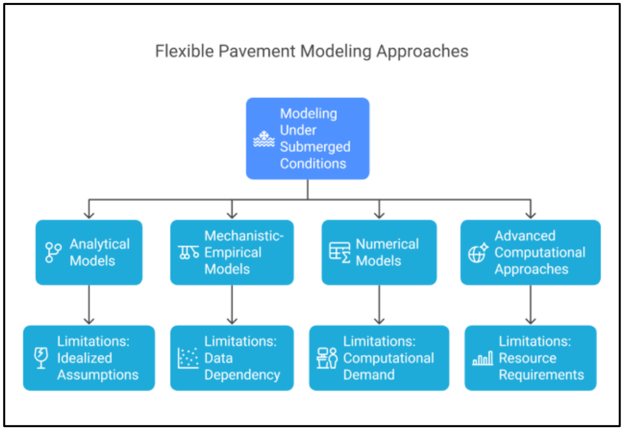
B. Mechanistic-Empirical Models

Mechanistic-empirical models bridge the gap between theory and empirical observations, offering improved insights into pavement behaviour under varying environmental and loading conditions. These models incorporate empirical adjustments to account for changes in material stiffness and moisture content, making them more adaptable than purely analytical frameworks. However, their reliance on extensive field data introduces challenges, particularly in regions with diverse climatic conditions or limited data availability. Additionally, M-E models typically simplify critical moisture-related phenomena, such as hydrostatic pressure buildup and capillary action, and cannot often simulate time-dependent deterioration processes. As a result, their predictions under prolonged submerged conditions are prone to error, particularly during extreme weather events.

C. Numerical Models

Numerical approaches, especially finite element models (FEM), have emerged as powerful tools for pavement analysis, enabling the simulation of complex interactions between mechanical loads and environmental factors. FEM allows for the detailed representation of material heterogeneity, non-linear behaviour, and the dynamic effects of water infiltration. These models can simulate the redistribution of wheel loads across saturated layers, accounting for pore pressure and reduced effective stress. However, their high computational demand and dependency on precise input parameters limit their widespread application. Moreover, numerical models often struggle to incorporate real-time field conditions or stochastic elements, which are essential for addressing the inherent variability in moisture distribution and its effects on pavement performance. Advanced Computational Approaches

The integration of multi-phase flow models and artificial intelligence (AI) methodologies represents the cutting edge of pavement modelling. Multi-phase flow models capture the interactions between water, air, and solid phases, providing a nuanced understanding of moisture dynamics and their impact on material properties. These models excel in simulating hydrostatic pressure effects and the redistribution of moisture under dynamic loading conditions. Meanwhile, AI and machine learning (ML) approaches enhance predictive accuracy by analysing large datasets of pavement performance under varied conditions. These data-driven models can dynamically update predictions based on real-time inputs, offering a significant advantage in monitoring and maintenance planning. However, these approaches require extensive, high-quality datasets and computational resources, and their implementation in practical scenarios remains a work in progress. Fig. 7 presents various flexible pavement modelling approaches under submerged conditions. It categorises these approaches into four main types: analytical models, mechanistic-empirical models, numerical models, and advanced computational approaches. Each model type has specific limitations, including idealised assumptions, data dependence, computational demands, and resource requirements. The diagram highlights the challenges of modelling pavement performance under submerged conditions, emphasising the need to balance accuracy and feasibility when selecting a model.



[Fig.7: Flexible Pavement Modelling Approaches Under Submerged Conditions]

D. Emerging Needs and Future Directions

A critical gap across all existing models is their limited integration of climate change projections. Rising water tables, increased rainfall, and more frequent flooding events necessitate the development of resilient pavements and predictive models that account for these evolving conditions. Furthermore, life-cycle cost analysis is seldom embedded in these models, leaving policymakers without comprehensive tools to evaluate the economic implications of moisture-resilient designs. Advanced modelling strategies, such as coupling field sensor data with real-time computational simulations, offer a promising path forward. By integrating moisture-flow dynamics, material degradation processes, and stochastic variability, future models can provide a holistic understanding of pavement behaviour under submerged conditions. In summary, while classical analytical and empirical models provide baseline expectations, they uniformly lack direct treatment of moisture's dynamic effects. FEM offers a partial solution but is limited by data and computational needs. Thus, no existing approach fully addresses the integration of wheel load and moisture, highlighting a clear research gap.

IX. DISCUSSIONS AND UNIQUE CONTRIBUTIONS

This paper investigates the combined effects of moisture and wheel load on the deterioration of flexible pavements, emphasising that water ingress significantly accelerates damage mechanisms such as rutting, fatigue cracking, and stripping. Unlike studies that isolate load or environmental impacts, this review integrates both to assess finite element models (FEM) and their limitations, particularly under submerged conditions. While analytical models offer simplicity and efficiency, they cannot handle the complexities arising from moisture. Mechanistic-empirical models provide realistic predictions but fall short in simulating dynamic moisture effects. FEM excels at capturing complex interactions but is hindered by high computational demands and uncertainties in material properties. Emerging multi-phase flow models and AI/ML tools show promise for enhancing predictive accuracy but require robust data, validation, and resources. The paper underscores the need for moisture-resistant pavement designs that incorporate improved drainage, resilient materials, and construction methods, while advocating for climate-resilient infrastructure, life-cycle cost analysis, and the integration of real-time monitoring with advanced simulations to inform sustainable and adaptive pavement systems.

X. CONCLUSION

A. Summary of Key Findings

This review has highlighted the critical impact of wheel load on flexible pavement performance, particularly the detrimental effects of submergence. Water infiltration into pavement structures leads to significant loss of mechanical integrity, accelerating deterioration through mechanisms such as rutting, fatigue cracking, and stripping. The interplay between wheel loads and submerged conditions necessitates a thorough understanding of the underlying mechanics, as conventional modelling approaches often fall short of capturing the complexities introduced by moisture dynamics. Among the modelling techniques explored, finite element modelling (FEM) and mechanistic-empirical approaches are the most effective for simulating the nuanced behaviour of submerged pavements under varying load conditions.

B. Implications for Pavement Design and Maintenance

The findings of this review carry significant implications for pavement design and maintenance strategies. It is crucial to incorporate moisture-resistance measures in the design of flexible pavements, particularly in regions prone to flooding or waterlogging. This could involve improved drainage systems, moisture-resistant materials, and innovative construction techniques to enhance the overall resilience of the pavement structure. Furthermore, the adoption of advanced modelling techniques is imperative for developing more robust infrastructure capable of withstanding the combined impact of wheel loads and moisture exposure. Enhanced modelling approaches can facilitate informed decision-making regarding maintenance schedules and rehabilitation strategies, ensuring the longevity and safety of transportation networks.

C. Future Research Directions

Looking ahead, there is a pressing need for further experimental data, particularly from field studies under submerged conditions. Such data will be invaluable for validating and refining existing models, enabling more accurate predictions of pavement behaviour in real-world scenarios. Additionally, future research should explore the development and application of new materials and technologies specifically designed to withstand the dual challenges posed by wheel loads and moisture. Investigating the potential of alternative binders, innovative drainage solutions, and advanced composites may offer promising avenues to enhance pavement performance and resilience. By addressing these research gaps, the field can move toward more sustainable and effective solutions for managing the impacts of submerged conditions on flexible pavements.

DECLARATION STATEMENT

Some of the references cited are older, noted explicitly as [10], [21], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [55] and [56]. However, these works remain significant for the current study, as they are pioneering in their fields.

As the article's author, I must verify the accuracy of the following information after aggregating input from all authors.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been funded by any organizations or agencies. This independence ensures that the research is conducted objectively and without external influence.
- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate with supporting documentation.
- **Data Access Statement and Material Availability:** The adequate resources of

this article are publicly accessible.

- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

REFERENCES

1. D. M. Dilip and G.L. Sivakumar, "System reliability-based design optimisation of flexible pavements using adaptive meta-modelling techniques, vol 367, 2023, DOI: https://doi.org/10.1016/j.conbuildmat.2023.130351
2. M. Asim, M. Ahmad, M. Alam, S. Ullah, M. J. Iqbal, and S. Ali, "Prediction of rutting in flexible pavements using finite element method," Civil Engineering Journal, vol. 7, no. 8, pp. 1310–1326, 2021, doi: https://doi.org/10.28991/cej-2021-03091727
3. E. Asres, T. Ghebrab, and S. Ekwaro-Osire, "Framework for design of sustainable flexible pavement," Infrastructures, vol. 7, no. 1, 2022, DOI: https://doi.org/10.3390/infrastructures7010006
4. B. Ban, J. K. Shrestha, R. Pradhananga, and K. C. Shrestha, "Three-dimensional analysis of flexible pavement in Nepal under moving vehicular load," Advances in Computational Design, vol. 7, no. 4, pp. 371–393, 2022, DOI: https://doi.org/10.12989/acd.2022.7.4.371
5. H. Alimohammadi, V.R. Schaefer and J. Zheng. Performance of geosynthetic-reinforced flexible pavement: A review of full-scale field studies. Int. Pavement Res. Techol.14, 30-42 (2021) DOI: https://doi.org/10.1007/S42947-020-0019-Y
6. S. Bhandari, X. Luo, and F. Wang, "Understanding the effects of structural factors and traffic loading on flexible pavement performance," International Journal of Transportation Science and Technology, vol. 12, no. 1, pp. 258–272, 2023, DOI: https://doi.org/10.1016/j.ijtst.2022.02.004
7. National Highway Authority, Pavement Design Report (Revised) Peshawar-Torkham Section-I Consultancy Services for Feasibility Study and Preliminary Design of Peshawar-Kabul Motorway, Associated Consultancy Centre (Pvt.) Ltd. (ACC), SAMBO Engineering Co. Ltd., ACE-TES & Assign, Sept. 2018. http://consultacc.com/wp-content/uploads/2018/05/List-of-Projects-Seprated-4.pdf
8. Y. Deng, X. Luo, Y. Zhang, and R. L. Lytton, "Evaluation of flexible pavement deterioration conditions using deflection profiles under moving loads," Transportation Geotechnics, vol. 26, 2020, DOI: https://doi.org/10.1016/j.trgeo.2020.100434
9. V. Gladkikh, E. Korolev, V. Gladkikh, and I. Sukhachev, "Viscosity of plasticised sulphur-extended asphalt: two-factor sequential optimisation," MATEC Web of Conferences, vol. 106, p. 03013, 2017, DOI: https://doi.org/10.1051/matecconf/201710603013
10. R. Khan, J. Grenfell, and A. Collop, "Micromechanical modelling of typical Dense Bitumen Macadam (DBM) from laboratory testing and X-ray Computed Tomography (CT)," Construction and Building Materials, vol. 77, pp. 1–6, 2015, DOI: https://doi.org/10.1016/j.conbuildmat.2014.12.028. The works remain significant, see the declaration
11. Konstantinos Gkyrtis "Pavement analysis with the consideration of unbound granular material non-linearity Department of Civil Engineering, Democritus University of Thrace (D.U.Th), 67100 Xanthi, Greece (2023) DOI: https://doi.org/10.3390/designs7060142.
12. S. Rahman, A. Ahmed and S. Erlingsson (2025) "Responses of a thin flexible pavement loaded with tyres of various dimensions and configurations, Road Materials and Pavement Design, DOI: https://doi.org/10.1080/14680629.2025.2489019.
13. N.D.Beskou and E.V. Muho "Review on dynamic response of road pavement to moving vehicle loads; DOI: https://doi.org/10.1016/j.solidyn.2023.108249.
14. M. Xianyong; S. Lingxiao; "S. Chundi "Probability distribution of asphalt pavement responses and performance", Applied Science; Basel vol. 13, iss. 2, (2023): 715. DOI: https://doi.org/10.3390/app13020715
15. A.K. Singh and J.P. Sahoo "Rutting prediction models for flexible pavement structure: A review of historical and recent developments. DOI: https://doi.org/10.1016/j.jtte.2021.04.003
16. S. Elhamrawy, M. Moharram and U. Heneash "The effect of truck axle loads and tyre pressure on the responses of flexible pavement" article 16, vol.45, issue 3. DOI: https://doi.org/10.21608/erjm.2022.145003.1187.
17. W. Jongxu, D. Zejiao, X. Ke, U. Shafi, W. Donghao and L. Yiheng. Numerical simulation of mechanical response analysis of asphalt pavement under dynamic loads with non-uniform tyre pavement contract stresses. DOI: https://doi.org/10.1016/j.cpnbuildmat.2022.129711.
18. M. Asim, R. Khan, A. Ahmed, and Q. Ali, "Numerical modelling of nonlinear behaviour of asphalt concrete," International Journal of Advanced Engineering Research and Development, vol. 5, no. 10, pp. 1–10, Oct. 2018, DOI: https://doi.org/10.21090/IJAERD.85114.
19. A. K Singh and J. P. Sahoo, "Rutting prediction models for flexible pavement structures: a review of historical and recent developments," Journal of Traffic and Transportation Engineering (English Edition), vol. 8, no. 3, pp. 315–338, 2021, DOI: https://doi.org/10.1016/J.JTTE.2021.04.003.
20. T. M. Tiza, O. Mogbo, S. K. Singh, N. Shaik, and M. P. Shettar, "Bituminous pavement sustainability improvement strategies," Energy Nexus, vol. 6, p. 100065, Jun. 2022, DOI: https://doi.org/10.1016/j.nexus.2022.100065
21. A. Tiliouine, K. Sandjak, C. Y. Ali Haimoud, and M. Hammoutène, "Effects of interface condition on performance of road pavements with non-linear granular materials," Advanced Materials Research, vol. 587, pp. 102–106, 2012, DOI: https://doi.org/10.4028/www.scientific.net/amr.587.102., works remain significant, see the declaration
22. S. Varma and M. E. Kutay, "Viscoelastic nonlinear multilayered model for asphalt pavements," Journal of Engineering Mechanics, vol. 142, no. 7, pp. 1–11, 2016, DOI: https://doi.org/10.1061/(ASCE)EM.1943-7889.0001095.
23. P. J. Yoo, "Flexible pavement dynamic responses analysis and validation for various tyre configurations," PhD dissertation, Univ. of Illinois at Urbana-Champaign, Illinois, USA, 2007. https://www.semanticscholar.org/paper/Flexible-Pavement-Dynamic-Response-Analysis-and-for-Yoo/a34318e66e58b920779aa263cb66fc66e5f139af. The works remain significant, see the declaration
24. V. A. Sawant, V. A. Patil, and K. Deb, "Effect of vehicle-pavement interaction on dynamic response of rigid pavements," Geomechanics and Geoengineering: An International J., vol. 6, no. 1, pp. 31–39, 2011.
25. Z. Lu and H. Yao, "Effects of the dynamic vehicle-road interaction on the pavement vibration due to road traffic," J. of Vibroengineering, vol. 15, no. 3, pp. 1291–1301, 2013. DOI: https://doi.org/10.1080/17486025.2010.521591. The works remain significant, see the declaration
26. P. D. Hunt and J. M. Bunker, Analysis of Unbound Granular Pavement Deterioration for use in Asset Management Modelling: A Literature Review, State of Queensland (Department of Main Roads), 2001. https://eprints.qut.edu.au/215882/. The works remain significant, see the declaration
27. S. Yang, S. Li, and Y. Lu, "Investigation on dynamical interaction between a heavy vehicle and road pavement," Vehicle System Dynamics, vol. 48, no. 8, pp. 923–944, 2010. DOI: https://doi.org/10.1080/00423110903243166. The works remain significant, see the declaration
28. A. T. Papagiannakis and M. S. Gujarathi, A Roughness Model Describing Heavy Vehicle-Pavement Interaction, Washington State Transportation Commission Final Research Report No. WA-RD 372.1, 1995. https://www.wsdot.wa.gov/research/reports/fullreports/372.1.pdf. Works remain significant; see the declaration
29. A. P. Wu and P. A. Shen, "Dynamic analysis of concrete pavements subjected to moving loads," J. of Transportation Engineering, vol. 122, no. 5, pp. 367–373, 1996. DOI: https://doi.org/10.1061/(ASCE)0733-947X(1996)122:5(367), The works remain significant, see the declaration
30. M. S. Mamlouk, "General outlook of pavement and vehicle dynamics," J. of Transportation Engineering, vol. 123, no. 6, pp. 515–517, 1997. DOI: https://doi.org/10.1061/(ASCE)0733-947X(1997)123:6(515), The works remain significant, see the declaration
31. A. Rutka and J. Sapragonas, "The role of a tyre in vehicle and road interaction," Transport, vol. 17, no. 2, pp. 39–45, 2002. https://www.tandfonline.com/doi/abs/10.1080/16483480.2002.10414009. The works remain significant, see the declaration
32. G. Lombaert and G. Degrande, "The experimental validation of a numerical model for the prediction of the vibrations in the free field produced by road traffic," J. of Sound and Vibration, vol. 262, no. 2, pp. 309–331, 2003. DOI: https://doi.org/10.1016/S0022-460X(02)01048-9, The works remain significant, see the declaration
33. H. H. Nassif and M. Liu, "Analytical modelling of bridge-road-vehicle dynamic interaction system," J. of Vibration and Control, vol. 10, no. 2, pp. 215–241, 2004.

DOI: https://doi.org/10.1177/1077546304033950. The works remain significant, see the declaration

34. A. T. Papagiannakis, H. M. Zelelew, and B. Muhunthan, "A wavelet interpretation of vehicle-pavement interaction," International J. of Pavement Engineering, vol. 8, no. 3, pp. 245–252, 2007. DOI: https://doi.org/10.1080/10298430701309378. The works remain significant, see the declaration
35. V. Sawant, "Dynamic analysis of rigid pavement with vehicle-pavement interaction," International J. of Pavement Engineering, vol. 10, no. 1, pp. 63–72, 2009. DOI: https://doi.org/10.1080/10298430802342716. The works remain significant, see the declaration
36. X. M. Shi and C. S. Cai, "Simulation of dynamic effects of vehicles on pavement using a 3D interaction model," J. of Transportation Engineering, vol. 135, no. 10, pp. 736–744, 2009. DOI: https://doi.org/10.1061/(ASCE)TE.1943-5436.0000045, The works remain significant, see the declaration
37. K. M. Xia, "A finite element model for tyre/pavement interaction: Application to predicting pavement damage," International J. of Pavement Research and Technology, vol. 3, no. 3, pp. 135–141, 2010. https://www.proquest.com/openview/bfadfd11e7d1d14a9e2506ccbcae3f8d/1?pq-origsite=gscholar&cbl=60371. The works remain significant, see the declaration
38. A. Taheri, E. J. Obrien, and A. C. Collop, "Pavement damage model incorporating vehicle dynamics and a 3D pavement surface," International J. of Pavement Engineering, vol. 13, no. 4, pp. 374–383, 2012. DOI: https://doi.org/10.1080/10298436.2012.655741. The works remain significant, see the declaration
39. G. Wang, R. Roque, and D. Morian, "Effects of surface rutting on near-surface pavement responses based on a two-dimensional axle-tire-pavement interaction finite-element model," J. of Materials in Civil Engineering, vol. 24, no. 11, pp. 1388–1395, 2012. DOI: https://doi.org/10.1061/(ASCE)MT.1943-5533.0000526, The works remain significant, see the declaration
40. P. Cao, C. Zhou, D. Feng, Y. Zhao, and B. Huang, "A 3D direct vehicle-pavement coupling dynamic model and its application on analysis of asphalt pavement dynamic response," Mathematical Problems in Engineering, pp. 1–8, 2013. DOI: https://doi.org/10.1155/2013/394704. The works remain significant, see the declaration
41. V. A. Patil, V. A. Sawant, and K. Deb, "2-D finite element analysis of rigid pavement considering dynamic vehicle-pavement interaction effects," Applied Mathematical Modelling, vol. 37, no. 3, pp. 1282–1294, 2013. DOI: https://doi.org/10.1016/j.apm.2012.03.034, The works remain significant, see the declaration
42. V. A. Patil, V. A. Sawant, and K. Deb, "3D finite-element dynamic analysis of rigid pavement using infinite elements," International J. of Geomechanics, vol. 13, no. 5, pp. 533–544, 2013. DOI: https://doi.org/10.1061/(ASCE)GM.1943-5622.0000255, The works remain significant, see the declaration
43. Y. Liu and Z. P. You, "Fundamental study on pavement-wheel interaction forces through discrete element simulation," International J. of Pavement Research and Technology, vol. 6, no. 6, pp. 689–695, 2013. DOI: https://doi.org/10.6135/ijprt.org.tw/2013.6(6).689, The works remain significant, see the declaration
44. H. Ding, Y. Yang, L. Q. Chen, and S. P. Yang, "Vibration of vehicle-pavement coupled system based on a Timoshenko beam on a nonlinear foundation," J. of Sound and Vibration, vol. 333, no. 24, pp. 6623–6636, 2014.l/, DOI: https://doi.org/10.1016/j.jsv.2014.07.016, works remain significant, see the declaration
45. N. D. Beskou, S. V. Tsinopoulos, and D. D. Theodorakopoulos, "Dynamic elastic analysis of 3-D flexible pavements under moving vehicles: A unified FEM treatment," Soil Dynamics and Earthquake Engineering, vol. 82, pp. 63–72, 2016. DOI: https://doi.org/10.1016/j.soildyn.2015.11.013
46. L. You, K. Yan, Y. Hu, and D. G. Zollinger, "Spectral element solution for transversely isotropic elastic multi-layered structures subjected to axisymmetric loading," Computers and Geotechnics, vol. 72, pp. 67–73, 2016. DOI: https://doi.org/10.1016/j.compgeo.2015.11.004
47. S. Chen, D. Wang, J. Yi, and D. Feng, "Analytical solution and distribution characteristics of mechanical response for elastic half-space body under hyperbolic paraboloid vertical load," in Functional Pavement Design, pp. 729–739, 2016. https://www.taylorfrancis.com/chapters/edit/10.1201/9781315643274-81/analytical-solution-distribution-characteristics-mechanical-response-elastic-half-space-body-hyperbolic-paraboloid-vertical-load-songqiang-chen-dongsheng-wang-junyan-yi-decheng-feng
48. L. You, K. Yan, Y. Hu, and W. Ma, "Impact of interlayer on the anisotropic multi-layered medium overlaying viscoelastic layer under axisymmetric loading," Applied Mathematical Modelling, vol. 61, pp. 726–743, 2018. DOI: https://doi.org/10.1016/j.apm.2018.05.020
49. A. A. Adili, "Study of Surface Drainage Runoff and Vertical Drainage of Flexible Pavement under Laboratory Wheel Track Test," Civil Engineering Research Journal, vol. 1, no. 1, Jul. 2017, DOI: https://doi.org/10.19080/cerj.2017.01.555553
50. H. Wang, M. Li, N. Garg, and J. Zhao, "Multi-wheel gear loading effect on load-induced failure potential of airfield flexible pavement," International Journal of Pavement Engineering, vol. 21, no. 6, pp. 805–816, Aug. 2018, DOI: https://doi.org/10.1080/10298436.2018.1511783
51. Y. Li, G. Song, and J. Cai, "Mechanical Response Analysis of Airport Flexible Pavement Above Underground Infrastructure Under Moving Wheel Load," Geotechnical and Geological Engineering, vol. 35, no. 5, pp. 2269–2275, May 2017, DOI: https://doi.org/10.1007/s10706-017-0242-8
52. F. Jebur, M. Fattah, and A. Abduljabbar, "Function and Application of Geogrid in Flexible Pavement under Dynamic Load," Engineering and Technology Journal, vol. 39, no. 8, pp. 1231–1241, Aug. 2021, DOI: https://doi.org/10.30684/etj.v39i8.1771
53. M. Tiza, "Sustainability in the civil engineering and construction industry: A review," Journal of Sustainable Construction Materials and Technologies, 2022, DOI: https://doi.org/10.14744/jscmt.2022.11
54. M. Y. Fattah, Shayma'a Abd. El-Ghany, and A. S. Abdaljabbar, "Analysis of the Performance of Flexible Pavement under the Effect of Wheel and Thermal Loads," Mağallaẗ al-handasaẗ wa-al-tiknūlūğiyā, vol. 28, no. 18, pp. 5782–5802, Sep. 2010, DOI: https://doi.org/10.30684/etj.28.18.14
55. C. Vale, "Influence of vertical load models on flexible pavement response—an investigation," International Journal of Pavement Engineering, vol. 9, no. 4, pp. 247–255, Aug. 2008, DOI: https://doi.org/10.1080/10298430701444977, works remain significant, see the declaration
56. M. Y. Abu-Farsakh and Q. Chen, "Evaluation of geogrid base reinforcement in flexible pavement using cyclic plate load testing," International Journal of Pavement Engineering, vol. 12, no. 3, pp. 275–288, Jun. 2011, DOI: https://doi.org/10.1080/10298436.2010.549565, works remain significant; see the declaration
57. K. Huang, I. Onifade, and B. Birgisson, "Calibration of mechanics-based pavement predictive framework for top-down cracking performance of flexible pavement considering wheel wander effect," Construction and Building Materials, vol. 306, p. 124792, Nov. 2021, DOI: https://doi.org/10.1016/j.conbuildmat.2021.124792
58. L. You, K. Yan, Y. Hu, J. Liu, and D. Ge, "Spectral element method for dynamic response of transversely isotropic asphalt pavement under impact load," Road Materials and Pavement Design, vol. 19, no. 1, pp. 223–238, Sep. 2016, DOI: https://doi.org/10.1080/14680629.2016.1230513
59. H. Abbas and K. Mahmud, "A parametric study of concrete runway pavement layers depression under impact load," Vestnik MGSU, no. 9, pp. 1206–1217, Sep. 2022, DOI: https://doi.org/10.22227/1997-0935.2022.9.1206-1217
60. P. Ren, Z.-L. Chen, L. Li, W. Gong, and J. Li, "Dynamic shakedown behaviours of flexible pavement overlying saturated ground under moving traffic load considering the effect of pavement roughness," Computers and Geotechnics, vol. 168, p. 106134, Apr. 2024, DOI: https://doi.org/10.1016/j.compgeo.2024.106134.

AUTHOR'S PROFILE

Jaja Christine Israel is an engineer specialising in Highway and Transportation Engineering. She holds a Master's degree in Civil Engineering from Rivers State University, where her research focused on pavement behaviour and highway materials. She is currently pursuing a Doctor of Philosophy (PhD) degree in the Department of Civil Engineering at the University of Nigeria, Nsukka, with research interests in pavement performance, wheel-load modelling, moisture-induced deterioration in flexible pavements, and the application of analytical and numerical modelling techniques in transportation infrastructure. Christine is a registered member of the Council for the Regulation of Engineering in Nigeria (COREN). Her professional experience spans several years in the construction and engineering sector, where she has contributed to the design, supervision, and evaluation of the road projects, drainage systems, and transportation infrastructure. She has worked with multidisciplinary teams to deliver civil engineering solutions aligned with safety, sustainability, and economic efficiency principles. Her academic and professional work reflects a strong interest in improving pavement resilience under challenging environmental and load conditions. She has undertaken research on flexible pavement behaviour under submerged conditions, material modification for moisture resistance, and advanced pavement modelling approaches. She is also engaged in ongoing studies to integrate climate-sensitive considerations into road infrastructure design. Christine has inspired and mentored young engineers through professional engagements, technical discussions, and academic collaborations. Her long-term career goal is to contribute to innovative, evidence-based engineering practices that enhance the durability and functionality of transportation systems in developing and emerging regions.

Professor Jonah Agunwamba is a renowned academic and expert in Water Resources and Environmental Engineering at the University of Nigeria, Nsukka. He's an accomplished author, having written over 300 technical articles and books, including fiction and non-fiction works. Agunwamba holds four patents and has received numerous awards for his outstanding contributions to academics and literature *Academic Background:* - Completed his degrees up to the doctorate level at the University of Nigeria, Nsukka - Served as Head of the Department of Civil Engineering, Dean of the Faculty, and Chairman of various committees at UNN *Research Interests:* - Water Resources and Environmental Engineering - Infrastructure Engineering and Asset Management - Reinforced Concrete Buildings *Awards and Recognition:* - Excellence Performance Award at UNN's 58th Founders Day - Certificate of Achievement for Best Engineering Academic Publication *Personal Life:* - Hails from Mbom-Ibeku, Umuahia, Abia State, Nigeria - Comes from a God-fearing family of eight - Values family, faith, and humanitarian work Agunwamba's work and legacy continue to inspire and impact the academic community and beyond. Phone No: 07078428098.
